Towards Commercial Fusion: Innovation, Technology Roadmapping for Start-ups, and Critical Natural Resource Availability

Thesis

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TOWARDS COMMERCIAL FUSION: INNOVATION, TECHNOLOGY ROADMAPPING FOR START-UPS, AND CRITICAL NATURAL RESOURCE AVAILABILITY

Thesis submitted for the degree of Doctor of Philosophy (PhD) in Engineering and Innovation

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The Open University

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This thesis is dedicated to two women who have shaped my life so profoundly: To my wife, Emily; who is my everything, and to the memory of my mother, Claire; to whom I owe everything.
Difficult to see, always in motion is the future

- Yoda, Star Wars
Abstract

Nuclear fusion, a potentially world-changing energy source, has been the subject of dedicated research for over half a century. With a focus on scientific research, development has principally been via publicly funded programmes led by government laboratories in which strategy and innovation are largely overlooked. Consequently, and without intention, the commercial aspects of development on such programmes are left until later, and routes that are not well-suited to commercialisation are pursued. The recent emergence of privately funded fusion start-ups with the explicit goal of commercialisation is disrupting the fusion innovation paradigm. The purpose of this thesis is to characterise the fusion start-up innovation approach and to apply Technology Roadmapping to help fusion start-ups overcome challenges in the commercialisation process. Strategic challenges in the availability, supply, and use of critical natural resources are specifically analysed. The research takes an interdisciplinary engineering systems approach, using mixed methods to connect innovation, technology management and strategy to the fusion paradigm. The thesis deploys innovation theory via contextual analysis, with parallels to the space exploration sector, to find that fusion start-ups operate on an agile innovation model. Technology Roadmapping is applied to a fusion start-up case study with Tokamak Energy Ltd, and the process is adapted to the hardware-based agile innovation approach. The impact of roadmapping on planning, innovation management and communication are examined. Via forecasting models and literature-based analysis, key commercial challenges for critical fusion resources – specifically deuterium, tritium, lithium-6, beryllium, lead and helium – are characterised. A new innovation space for commercial tritium breeding blankets is identified. In conclusion, this thesis characterises a paradigm shift in fusion commercialisation. It provides a framework for the innovation approach, an applied roadmapping process, and highlights key resource criteria yielding recommendations to drive commercial fusion missions forward.
Preface

This thesis contains approximately 112,000 words, including all text, captions, tables, and references. This complies with requirements of the research degree committee of the Open University, which has removed the capped word limit for this thesis. No part of the thesis has been previously submitted to any university for any degree, diploma, or other qualification. Copyright permission has been granted to use all figures presented in this thesis that were not created by the author. In some instances, figures from other publications have been redrawn by the author for the purposes of this thesis, with reference to the original publication. In one instance, copyright could not be obtained, and redrawing was not possible, and so the figure (Figure 6-6) has been redacted. Except for commonly understood or accepted ideas, or where specific reference is made, the research presented in this thesis is wholly the author’s work. However, as stressed in the acknowledgements, the author has received guidance and support from supervisors and research collaborators and, accordingly, parts of the thesis have informed a series of collaborative publications:


These publications relate to the work presented in this thesis but are not identical to it. Where common text appears, it is from the author’s contributions to those papers.

Finally, parts of this research were conducted with support and sponsorship from Tokamak Energy Ltd, UK. Specifically, the research presented in Chapter 4 of this thesis, and discussed in Chapter 5, is the result of a case study in which the researcher was based within Tokamak Energy Ltd. Unless specified, the method, results, analysis, and discussion presented in this research do not reflect the views or opinions of Tokamak Energy. The
other chapters of this thesis represent research that was not sponsored or supported by Tokamak Energy Ltd.
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However, while I am proud of myself for completing this thesis, naturally, I owe a debt of gratitude to so many people who have supported me – directly or indirectly, knowingly or unknowingly, and professionally or unprofessionally! It is important to me that I name each of them personally:

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Chapter 1. Introduction

1.1. Nuclear Fusion

1.1.1. Background

Nuclear fusion has long been heralded as the best solution to provide a clean source of energy that could be deployed worldwide to address the challenge of anthropogenic climate change and to meet rising world energy demand. Nuclear fusion is the same process that powers the sun and the stars in which, under enormous gravitational pressure and high temperatures, atomic nuclei can overcome nuclear repulsion to join together to create a heavier nucleus releasing massive amounts of energy in the process (Burbidge et al., 1957; Chen, 2011). The energy released from a fusion reaction is calculated using the relationship shown in equation 1.1, famously developed by Einstein (see (Wesson & Campbell, 2011)).

\[
E = \Delta m c^2
\]

Where \( E \) is energy, and \( \Delta m \) is the mass defect (between products and reactants), and \( c \) is the speed of light. In a fusion reaction, the mass of the product is fractionally less than the sum of the two atomic nuclei, and the mass defect is converted into energy. In a fusion reaction, this energy is transferred as kinetic energy carried by particles. The potential for fusion to provide an energy source is derived from the notion that the kinetic energy can be harnessed and turned into usable heat energy. However, recreating the conditions of a star on Earth is not possible, so the conditions have to be recreated by other means. In 1952, the conditions for fusion were created in the detonation of the world’s first thermonuclear bomb, Ivy Mike. While this represented an uncontrolled fusion reaction, it proved that nuclear fusion is possible on Earth. However, scientists attempting to create a controlled fusion reaction – for peaceful purposes – has since been the subject of dedicated research for well over half a century, primarily in government laboratories supported by research institutions and universities.

The primary focus of fusion research has been on trying to achieve the conditions required for fusion power “breakeven”. Breakeven is achieved when more power is produced from the fusion reactions in a plasma than the energy supplied to create the plasma; this is the power required to sustain the magnetic field and heat the plasma. In a fusion reactor, breakeven conditions are denoted as \( P_{\text{ fus}} = 1 \), or more commonly \( Q_{\text{ fus}} = 1 \). A fusion reactor that can produce a high \( Q_{\text{ fus}} \), e.g. a plasma with a \( Q_{\text{ fus}} \) of 10, can convert the excess fusion

---

1 \( Q_{\text{ fus}} \) is more common as it denotes energy, i.e. power multiplied by time.
energy into usable energy. The point at which breakeven is achieved can be characterised by the Lawson criterion, also known as the Fusion Triple Product, which is dependent on three key parameters in a fusion plasma: the density \( n \), the temperature \( T \), and the energy confinement time \( \tau_E \). The conditions required for fusion reactions can be expressed by the reactivity, which is defined as the probability of a reaction occurring, per unit time, per unit density of target nuclei. Figure 1-1 shows the reactivity of several potential fusion reactions.

![Figure 1-1](image_url)

*Figure 1-1  The probability of nuclear fusion reactions between light atomic nuclei (for averaged reactivity), reproduced under a Creative Commons license from (Torrisi, 2014). (Also known as “the Lawson diagram”).*

The plot in Figure 1-1 shows that D-T fusion – a reaction between two heavy atomic hydrogen nuclei deuterium (D) and tritium (T) – provides the most favourable conditions to achieve fusion breakeven. Accordingly, the majority of development has been focused on fusion reactors using D-T fuels, under the reaction shown in Eq. 1.2 (Wesson & Campbell, 2011; Chen, 2011).

\[
\text{Eq. 1.2 } 2D + 3T \rightarrow 4\text{He (3.52 MeV)} + 1n (14.06 \text{ MeV})
\]

\[\text{2 A D-T fusion neutron carries approximately 80% of the energy from the fusion reaction.}\]
Two primary approaches have been developed with the aim of achieving breakeven conditions, and mostly via D-T fusion. Magnetic confinement approaches are predicated on the use of magnets to control fusion plasmas which are positively charged and can thus be controlled by magnetic fields induced by electrical currents. The second approach is via inertial confinement in which fuel targets are compressed, typically via high power lasers, and heated to temperatures required for fusion. While substantial efforts have been placed on developing both approaches – as well as more recently on potentially promising alternative approaches combining the two – the development of fusion for energy has been focused mainly on a single magnetic confinement approach, the tokamak. Tokamak is a Russian acronym for Toroidalnaya Kamera Magnitnaya saksial'nym, which translates to “toroidal chamber with an axial magnetic field” (Takeda & Pearson, 2019). Accordingly, tokamaks use magnets surrounding a toroidal chamber to confine and drive plasma current. Unlike in inertial confinement approaches, the plasma is heated to fusion temperatures by external heating and current drive systems such as gyrotrons (Ikeda, 2009; Sánchez, 2014).

1.1.2. ITER and the public fusion programme

The success of tokamaks culminated in the conception of the ITER project. ITER, currently under construction, is a large tokamak that has been jointly developed by several major world nations, including the U.S., Russia, China and the European Union over the past three decades. A schematic of the ITER tokamak is shown in Figure 1-2.

![Schematic of the ITER tokamak with labels showing core technologies, adapted with permission from (ITER Organisation, 2019).](image)

3 For further information, refer to the article co-authored by the researcher (Takeda & Pearson, 2019).

4 See (Wurden et al., 2016).
ITER’s primary goal is to demonstrate fusion breakeven conditions. It is expected to produce a $Q_{\text{ fus }}$ of $\sim 10$, i.e. ten times more power will be produced in the ITER plasma than is used to create it (Sánchez, 2014). As such, it has long been considered that ITER will provide a key step towards the realisation of fusion energy. However, despite the importance of ITER, the project has been the subject of major cost overruns and delays. ITER was intended to be commissioned in the early 2010s, but the current schedule is for first plasma in 2025, with full power operation using a D-T fuel mix not expected until a decade later in 2035. As a result of the delays to the ITER project – which has consequently dominated the development focus for the majority of the world’s fusion scientists and institutions supporting the project – progress towards fusion breakeven has stalled. Figure 1-3 shows the progress up until 2000, after which domestic programmes switched to focus on the development of ITER.

![Figure 1-3](costley2019.png)

*Figure 1-3  Progress towards fusion breakeven conditions, including trendline to indicate the rate of progress and the projected operational date of ITER, reproduced under a Creative Commons license from (Costley, 2019).*

It is important to note that ITER is only a step on the route to the realisation of commercial fusion energy. While validating the fundamental principles of physics – its primary purpose, as well as demonstrating several key technologies – the machine will not produce usable energy. Next-step devices, typically named “DEMO”, are being developed to demonstrate energy production. DEMO devices are expected to overcome the many engineering challenges that remain, such as the development of advanced materials, fuel cycle systems to handle deuterium and tritium, and the development of advanced superconducting magnet technology. It is, therefore, only after DEMO that a first-of-a-kind fusion (FOAK) power plant can be built. As most DEMO projects are targeting a start date of 2050 or later, however, a FOAK fusion power plant is not likely until well into the second half of the 21st century (Edwin Cartlidge, 2017; Lopes Cardozo, Lange & Kramer, 2016; EUROfusion, 2018).
1.1.3. A shift in fusion: The emergence of fusion start-ups

Historically, due to the complexity and scale of the challenge, and the focus on developing scientific understanding, fusion development been in the domain of government-funded and coordinated R&D. Recently, however, delays to the ITER project, as well as the advent of new technologies and a new understanding of fusion physics, has stimulated the emergence of more than a dozen entrepreneur-led fusion start-ups backed by private investment. Fusion start-ups are pursuing concepts based on disruptive physics and disruptive technology. Some start-ups have adopted an approach closely linked to the tokamak and thus have a well-developed physics base (see [Gryaznevich & Sykes, 2017; Sorbom et al., 2015]), while others are focused on more novel physics approaches (see [Wurden et al., 2016; Laberge, 2016]). Most importantly, however, all start-ups are predicated on the idea that smaller, simpler and cheaper fusion reactors may accelerate the development of commercial fusion energy ([Costley, Hugill & Buxton, 2015; Whyte et al., 2016; Wurden et al., 2016; Laberge, 2016]).

Backed by private investment, fusion start-ups are thus focused on technology development and on demonstrating progress, despite lesser understanding of the physics. As such, fusion start-ups are making rapid progress in the early stages of R&D and are sharply focused on commercialisation. ITER is expected to demonstrate fusion breakeven in 2035, but several fusion start-ups are aiming to achieve this goal within the next decade. A shift in fusion is underway with both public and private efforts focused on being the first to achieve fusion breakeven; the race is on.

1.2. Research focus

In line with the focus on the development of robust fusion physics, and the need to demonstrate fundamental science and engineering principles that will enable future fusion reactors to be developed, there has been an overarching focus on technical research. Naturally, such emphasis on increasing scientific understanding has resulted in the fusion research adopting many established methodologies to solve complex technical problems. Consequently, there has been limited focus on the commercialisation of fusion. However, due to the recent emergence of fusion start-ups, there is a newfound drive to gain a better understanding of fusion commercialisation and – more broadly – fusion innovation.

This thesis will investigate research areas relating to the commercial aspects of fusion technology. Research gaps have been identified that focus on three distinct but related topics:

- Firstly, the shift in the approach to development driven by commercially-focused fusion start-ups is explored from the perspective of innovation.
- Secondly, fusion start-ups aiming to accelerate the commercialisation of fusion must develop programmes that allow for a focus on both the technology and the commercial aspects. As such, fusion start-ups require a form of innovation management to support their development.
- Finally, due to the focus of the majority of fusion research on the technical challenges, several key challenges relating to critical natural resources that may directly affect the commercialisation of fusion are characterised.

The following subsections describe each of these identified research gaps in more detail.

1.2.1. An innovation paradigm shift in fusion

Despite distinct differences in technical approach, all fusion start-ups share a common aim: to accelerate the development of fusion via less complex, smaller, cheaper devices, with the explicit goal of commercialisation. Compelled to show progress to investors and to demonstrate the viability of their concept, fusion start-ups are focused on demonstrating fusion breakeven before quickly moving to commercial prototypes. However, they must proceed with limited resources, and in some cases, an incomplete understanding of the core science and partially developed technologies. Start-ups must thus advance with an attitude to risk that is not primarily based on strategies of minimization and avoidance, but rather on the need to maintain forward momentum. They must expect failures from which to learn. By accepting a higher risk of failure, as well as by way of smaller and simpler machines, fusion start-ups have the potential to develop technology at higher speed and lower cost towards commercialisation (McCurdy, 2001). The innovation approach of fusion start-ups is thus one based on agile innovation, an approach used, for example, by the NASA COTS programme, and more recently by SpaceX, in the space sector (Rigby, Sutherland & Noble, 2018; McCurdy, 2001).

Publicly-funded government-led fusion programmes have historically, and by contrast, adopted an approach that focuses on first achieving a high degree of scientific understanding to enable the resolution of key technical challenges before proceeding, i.e. an aversion to risk. Accordingly, to achieve greater technical certainty necessitates greater emphasis on the technology challenges and thus, the broader challenge of commercialisation is left until much later. As such, the fundamental difference between public programmes and fusion start-ups is not just in the technical approach to fusion – that is, the reactor concept – but in the overall approach to innovation.

---

5 Innovation is defined in this thesis as “invention plus exploitation”.
Fusion start-ups are thus disrupting the existing fusion paradigm, upending the way in which innovation is approached by the public fusion programme. As a relatively new phenomenon, the emergence of fusion start-ups has not been explored from the perspective of innovation. Further still, the development of fusion in general, i.e. the public fusion programme, has not been characterised in the context of innovation. Both are, of course, linked and the shift from the public fusion programme approach to the start-up approach is here identified as a research gap. The innovation paradigm shift will thus be explored as a topic of this thesis.

1.2.2. Innovation management in fusion start-ups

Whilst fusion start-ups are found to be inherently different in their innovation approach to public fusion programmes, as a technology, fusion is still at an early stage of development. As such, fusion start-ups are predominantly focused on science and technology. One of the primary drivers for fusion start-ups is to develop technology for commercialisation. The management of the process to take technology to market is not organic, nor is it simple. Companies or organisations engaged in complex technology development inevitably operate in a changing environment where external developments beyond their control occur and potentially influence the intended future commercialisation path and even the long-term goal(s).

Several approaches collectively known as “Futures” methods can support planning in situations of such uncertainty and help to guide the innovation process in a number of ways (see (Gordon, 1992; Lindgren & Bandhold, 2003; Martin & Irvine, 1989)). An innovation management method for fusion start-ups should be able to support planning in conditions of uncertainty and ensure that technical and commercial drivers essential for successful innovation are considered at all stages. Technology Roadmapping is one such method that supports the planning of key activities required to develop technology(s) and take it to market. Principally, it can facilitate innovation through alignment of technology or product development needs with capabilities and commercial goals (Kostoff & Schaller, 2001; Albright & Kappel, 2003; Phaal, Farrukh & Probert, 2010; International Energy Agency, 2014).

Technology Roadmapping has been applied to a variety of industrial contexts, including for fusion. However, such roadmaps have been developed as a guide for the public fusion programmes, e.g. see (EUROfusion, 2018), which is later discussed. Roadmapping has previously been developed to support agile innovation (see (Ozaki, de Vasconcellos & Bengtsson, 2015; Carlos, Amaral & Caetano, 2018; Phaal, Simonse & Den Ouden, 2008)), but it has not been applied to complex and early-stage hardware-based technology with long time horizons, high risk and high costs such as fusion start-ups. Application of
roadmapping to fusion thus provides value in an industrial context (to fusion start-ups and to the fusion research space more broadly) and to the roadmapping literature (roadmapping for innovation management and application to a novel problem).

1.2.3. Natural resources for fusion: a key challenge to commercial realisation

As mentioned, fusion research has predominantly focused on future technology challenges. As such, many of the technological challenges are well-characterised and in sharp focus through various dedicated research programmes around the world. The challenges associated with technology development have an overarching focus; develop the technology first and bring to commercial market later. Despite this, challenges that affect the commercial viability of fusion are well-known. In particular, they relate to the need to develop a reactor that can sustain a plasma to enable energy generation. As such, this inherently drives reactor and technology development that is cost-effective and easy to build, which in turn requires the development of efficient plasma-relevant technologies, such as magnets. However, there are several longer-term challenges that are likely to affect the commercial viability of fusion. During the early stages of the development of a Technology Roadmap for Tokamak Energy (see 1.2.2), several of these challenges were characterised. As a result, aligned with the need to understand barriers to commercialisation, it was determined that a specific challenge – natural resources for fusion – should be explored in greater depth. The results from a deeper dive into one of many issues could thus inform future development and can be a key input for roadmapping.

The fuels for nuclear fusion are often described as “unlimited” and ubiquitous, which will enable fusion to be deployed around the world (see (Bradshaw, Hamacher & Fischer, 2011; Sánchez, 2014; Ward, 2007; Tokimatsu et al., 2003; ITER Organisation, 2020)). However, such claims are predicated on the content of important isotopes in seawater. Deuterium, one component of the D-T fuel mix, is indeed abundant in seawater. Tritium, on the other hand, does not occur naturally on Earth in any significant quantity. In small quantities, tritium is produced in specific types of fission reactor (heavy water reactors), which can be used for fusion experiments. In the long-term, however, tritium for commercial fusion programmes can be produced from lithium which, when interacting with a neutron – arising from the D-T fusion reaction, can undergo fission to produce one helium and one tritium atom. Tritium will be produced in fusion reactors by way of a lithium-filled “tritium breeding blanket”. Consequently, fusion reactors depend on lithium, rather than tritium, as a primary fuel.

Like deuterium, lithium is abundant in seawater and in terrestrial deposits. However, tritium breeding blankets are also dependent on several other critical materials. Firstly, natural lithium contains approximately 92.6% lithium-7 and 7.4% lithium-6. However, due to the
nuclear properties of the two lithium isotopes, it is lithium-6 which has a higher affinity for producing tritium. In consequence, most tritium breeding blanket designs require enrichment of natural lithium to increase the fraction of lithium-6. Furthermore, to achieve effective fuel production in a fusion reactor, one tritium atom must be produced per one D-T fusion neutron. Due to losses in the reactor, neither natural lithium nor lithium enriched in lithium-6 can provide a tritium breeding ratio (TBR) of above unity. As such, materials with special nuclear properties – that can enhance the neutron yield (neutron multipliers) – are also necessary. The two most common neutron multipliers are beryllium or lead. Finally, to remove the heat from the tritium breeding blanket – which also serves an important dual purpose as the way of harnessing the energy from the fusion reaction as heat – a coolant is required. Helium or water are typically selected as coolants, with the former preferred due to its high-temperature performance and potential to increase reactor efficiency. Therefore, the ubiquity of deuterium and lithium in seawater is an oversimplification of the fusion fuel cycle.

Several studies have explored the availability of the resources required for the D-T fuel cycle. Such studies are carried out at a conceptual level and only serve to identify the issue and do not explore the problems in depth. In particular, several of the resources described in the previous paragraph have the potential to limit the commercialisation of fusion. For each of the resources, there is a range of challenges associated with the availability, supply and use that are not fully understood. The resources required for the D-T fuel cycle may affect the commercialisation of fusion, and thus understanding the extent of such issues is a key research gap. In particular, the following resources – which, in the context of this thesis, are all considered as fuels for fusion – have been identified from the literature (see (Bradshaw, Hamacher & Fischer, 2011; Holdren, 1978; Rhinehammer & Wittenberg, 1978; Ward, 2007; Tokimatsu et al., 2003)):

- Deuterium
- Tritium (for experiments)
- Lithium (specifically lithium-6)
- Beryllium
- Lead
- Helium

The specific challenges as regards each of these resources from the perspective of commercialisation are explored in this research.
1.3. **Research approach**

1.3.1. **Research Questions**

This thesis will explore three distinct themes based on the research gaps identified previously in 1.2, specifically:

1. *The shift in the approach to innovation by fusion start-ups*

2. *Innovation management methods to support fusion start-ups navigate the commercialisation process*

3. *The commercial challenges associated with the fuel resource required for the realisation of fusion*

Consequently, this thesis will address three primary research questions focused on each of these topics (research question 2 is split into two parts):

1. *What are the differences in the approach to innovation by government-led publicly-funded fusion programmes and privately-funded fusion start-ups?*

2. *Research question 2 is split into two parts which are both focused on innovation management in the fusion start-up context:*
   
   **A.** *Can an innovation management method be adapted to fusion start-ups – which operate on an agile innovation model – to support the commercialisation process?*
   
   **B.** *Consequently, how can the development and application of Technology Roadmapping (as an innovation management method) support fusion start-ups?*

3. *What are the issues surrounding the availability, supply and use of critical fuels for D-T fusion, and how do they affect the route to commercialisation?*

1.3.2. **Research Methodology**

This research is interdisciplinary, drawing on several methodologies and methods from several different disciplines\(^6\). The first research question is addressed by exploring the

---

\(^6\) The distinction between methodology and method is often confused. In this thesis, “method” refers to a specific research tool that is used to answer a research question, whilst “methodology” is defined as the way in which the research is conducted.
issue from the perspective of existing innovation literature which is applied to the fusion context, through critical review and analysis. The second is addressed via an action research methodology\textsuperscript{7} with the researcher embedded in a fusion start-up as a case study, using Technology Roadmapping as a method to facilitate an engineering systems approach\textsuperscript{8}. The third research question is addressed via mixed (both quantitative and qualitative) methods.

Research objectives are outlined to address the research questions. Accordingly, research methodologies and specific methods are chosen according to their suitability to meet the research objectives. The overall research approach – the way in which each of the research questions is answered – is outlined in Table 1-1.

<table>
<thead>
<tr>
<th>Research Question</th>
<th>Research Approach (how the research question is answered)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Review and analysis of both the innovation and fusion literature providing an application of theory to the industrial context.</td>
</tr>
<tr>
<td>2A</td>
<td>Exploration of suitable innovation management methods for the research. The selected method is adapted in an industrial context via action research (with the researcher embedded in a fusion start-up case study).</td>
</tr>
<tr>
<td>2B</td>
<td>Analysis of outcomes via an expert-led review of the process developed, with the outputs of research in 2A explored and discussed with reference to the literature.</td>
</tr>
<tr>
<td>3</td>
<td>Forecasts for natural resource availability and supply, with results analysed and discussed in the context of broader policy issues, including in areas external to that explored in the existing fusion literature (e.g. resource mining).</td>
</tr>
</tbody>
</table>

Table 1-1  \textit{Research questions and how they are answered in this thesis}

\textsuperscript{7} Action research as a methodology is detailed in section 3.5.

\textsuperscript{8} The definition and use of the term “systems” in this thesis is discussed in section 2.2.3.
1.4. **Structure of this thesis**

The structure of the thesis is shown overleaf in Figure 1-4, and the content is as follows:

- **Chapter 2** details the innovation paradigm shift to fusion start-ups, exploring how fusion start-ups are different from the public programme through comparison of the innovation literature, with specific reference to agile, lean and open innovation.

- **Chapter 3** explores futures methods to support planning and innovation management. From a review of techniques, Technology Roadmapping is selected as a suitable method to be applied to support fusion start-ups.

- **Chapter 4** details the Technology Roadmapping process developed with a fusion start-up case study Tokamak Energy Ltd. The process and roadmap developed are presented objectively as a framework useful for all fusion start-ups.

- **Chapter 5** analyses aspects of the developed roadmapping process to assess its usefulness and to evaluate how it can be improved.

- **Chapter 6** explores the supply of tritium for fusion R&D in the near-term and characterises challenges with deuterium supply for commercial fusion.

- **Chapter 7** assesses the challenges associated with the availability, supply and use of critical resources for tritium breeding blankets, providing a commercial focus on a problem that has until now, largely been explored from the technical perspective.

- **Chapter 8** collates the findings and addresses all research questions, outlining key contributions to knowledge, limitations and recommendations.
Figure 1-4  Structure of this thesis.
Chapter 2. An innovation paradigm shift: Fusion start-ups

This chapter will address research question 1:

What are the differences in the approach to innovation by government-led
Publicly-funded fusion programmes and privately-funded fusion start-ups??

The research objective is to review the development approach of public fusion programmes and fusion start-ups through contextualisation with reference to the innovation literature. Through analytic characterisation, this chapter will introduce concepts and theory from existing research fields which have not been considered before in fusion research. The findings are presented at the end of this chapter but collated in Chapter 8 (conclusions).

Aspects of, and content presented in, this chapter can be found in part or whole in the following peer-reviewed publication, published in the journal Technology Forecasting and Social Change:

2.1. The public fusion programme

2.1.1. History

The early years of fusion development were characterised by a desire to shift an early Cold War nuclear arms race into something that instead resembled social value. President Eisenhower initiated the US ‘Atoms for Peace’ programme in 1952 as a “swords into ploughshares” transformation. Famously, the development of ZETA (Zero Energy Thermonuclear Assembly) at Harwell, UK was based on previous experiments from the nuclear weapons laboratory at Aldermaston, UK. The ZETA machine, like its counterparts in the Soviet Union and the U.S., was an experiment carried out in secrecy until 1958 when it was published that ZETA had achieved fusion, see (ITER Organisation, 2018). Famously, it was found that this claim was erroneous, but the publication of the error meant that fusion moved from being a project of high secrecy to becoming arguably one of the most open research fields today. Thus, ZETA, despite only short-lived success as a viable fusion reactor concept, facilitated a shift in focus towards a civil fusion programme which grew in strength and gradually assumed remarkable prominence in international relations. Around a decade after ZETA, the success of a Soviet design sparked excitement and shifted the development of fusion globally to focus almost solely on a single technical approach: the tokamak. Several decades after, the international focus and progression of the tokamak culminated in the creation of the internationally coordinated project. A key step in the development of tokamak fusion was reached when an agreement made between the leader of the Soviet Union Mikhail Gorbachev and President of the United States of America Ronald Reagan in 1985 for the joint development of fusion via what was known as the International Thermonuclear Experimental Reactor (now known only as ITER) (ITER Organisation, n.d.). The mission was subsequently joined by several other international partners, including the European Union, China and India.

2.1.2. The ITER project

ITER is a large tokamak with a plasma volume of about 1000 m³, an estimated projected cost of about $20B, and a design-to-operation time in the order of 30 years (Clery, 2015; Locatelli, 2017). ITER was designed with the goal of becoming the first device to achieve conditions of fusion power breakeven; the moment at which the power produced by the fusion reaction is the same as that supplied to it (via D-T fusion). ITER was designed based on physics scaling from previous experimental results which suggested that increased plasma size in tokamaks resulted in an increase in power gain, i.e. bigger is better. This condition was also in line with economic analyses which, at the time, dictated that a fusion power plant would need to use large plasma volumes, and produce energy in the order 1
GWe to be commercially viable (see Maisonnier et al., 2005; Ward, Cook & Knight, 2001)). However, there were a variety of other factors that led to the fusion community to pursue increasingly large, complex and expensive devices that typically take several decades to construct and operate (Whyte et al., 2016). Alongside the perceived technical and economic rationale, the cost and scale of the project, as well as the political importance, led to a shift in the organisational culture, as with ZETA. Principally, ITER set fusion research on a pathway that demanded focus on only the single technical approach of the tokamak, snubbing other potentially promising approaches. Accordingly, in doubling-down on the tokamak, the prospect of the ITER project being a clear and unequivocal failure was something to be avoided at all costs. To proceed with technical certainty to achieve this, however, requires rigorous planning to qualify all parts and processes. As a result, delays and cost overruns can accumulate. Research suggests that the majority of megaprojects are over budget, delayed, and – in hindsight – have operational results that often rarely justify the implementation of the project (Locatelli, 2017; Flyvbjerg & Molloy, 2011). ITER is indeed a megaproject, subject to the same cost overruns and delays that affect the majority of all technology megaprojects. The original schedule planned ITER to be commissioned in the early 2010s and to achieve breakeven by around 2016 (see Glugla et al., 2007; McLean, 2002)). However, due to delays, ITER is now expected to achieve fusion breakeven in 2035 or later (ITER Organisation, n.d.).

Walker and Haines argue that were ITER treated as a wholly scientific endeavour for cultural benefit with unspecified (but certainly probable) economic benefits, akin to those from the CERN programme or even the Apollo missions, then cost overruns and delays might be justified (Walker & Haines, 1997). However, the ITER project has altogether been positioned differently. It has been heralded as the pathway to commercially viable clean fusion energy, rather than just as a scientific and political endeavour. Ultimately, of course, the operation and contribution of ITER could still be deemed a success in hindsight, judged by its contribution to society (Shapira & Berndt, 1997; Cooper, 2003). In contrast, while spin-off technologies arose from the Apollo programme, for example, the primary goals were principally for political and scientific interest, not for commercial gain. ITER, on the other hand, is intended to lead to a commercial product. Despite this, and in part based on the perceived need to have a high degree of scientific understanding to resolve complex technical challenges, comparatively little attention has been paid to the broader challenge of the commercialisation aspects of fusion development⁹.

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⁹ Commercialisation is defined here as a set of activities associated with preparing an invention (a product or technology) for market (Tidd & Bessant, 2018). Commercialisation thus describes the process of innovation – the exploitation of invention – to take a technology to market; see 2.2.1.
As early as 1981, it was suggested that fusion based on large tokamaks would never result in commercial success due to the scale and complexity (and therefore cost) (Carruthers, 1981). This perspective was echoed and further developed subsequently by Kulcinski and Santarius (Kulcinski & Santarius, 1998), the Electric Power Research Institute (EPRI) (Kaslow et al., 1994) and Walker and Haines (Walker & Haines, 1997). Specifically, they suggested that the scale and complexity of fusion concepts following the prototype of ITER were “pricing [fusion] out of the game” (Kulcinski & Santarius, 1998) and would not lead to commercially viable fusion energy. All of these critics advocated that commercialisation be emphasised in the pursuit of simpler (but not necessarily smaller) and low-cost experimental reactors. Further, they all advocated exploration of prospective routes to commercialisation that are not solely focused on electricity generation (see, for instance, (Nuttall, Glowacki & Clarke, 2005)). The scientific basis at the time suggested that large tokamaks were necessary to achieve fusion and ultimately to provide large-scale commercial electricity production as well. Despite the rationale, which did not conflict with the scientific basis or even the ultimate commercial goal but rather questioned the approach to development (and intrinsically, as shall be discussed, the innovation approach), the direction of ITER and its position at the centre of fusion research remained unchanged. Well over two decades since its inception, significant time, effort and capital has been invested into ITER. However, in an attempt to increase the chance of ultimate success – which is still nevertheless uncertain, principally due to the lack of understanding of burning plasma physics – has, somewhat paradoxically increased the chance of commercial failure. As contended by Lopes-Cardozo (Lopes-Cardozo, 2019; Lopes Cardozo, Lange & Kramer, 2016), and as will be shown in the incumbent analysis, ITER represents an ineffective approach to innovation that will not lead to commercial fusion.

2.1.3. A change in fusion

Owing perhaps to the central focus on ITER, but certainly, due to the scale and complexity of the challenge, the conventional view has been that the development of fusion is deemed possible only by means of government-funded and coordinated science projects. However, over the past decade, fusion start-ups, backed by private investment and pursuing new concepts, have started to challenge the incumbent paradigm. In this thesis, it is contended that publicly-funded fusion programmes, particularly ITER – which is not expected to yield a commercial fusion power plant for decades – are being disrupted by fusion start-ups. Whilst there are obvious technical and economic drivers behind the shift towards fusion start-ups (principally, the exploration of promising concepts that may result in simpler fusion reactors at lower cost), there is also evidence that it is underpinned by a change in the approach to innovation. This chapter will explore fusion in the context of innovation, first
analysing the innovation approach of public fusion programmes, before characterising and contrasting with the fusion start-up innovation approach.

2.2. Innovation

Innovation in fusion is a largely underexplored area, and few publications in the fusion literature refer to “innovation”, at least not with reference to it as the subject of a dedicated field of research. Largely, fusion has not been explored in the context of innovation. However, innovation as a concept is commonly misunderstood.

2.2.1. What is innovation?

There are many definitions of innovation. Tidd and Bessant define innovation as the “process of turning opportunity into new ideas and of putting these into widely used practice” (Tidd & Bessant, 2018), which stems from one of the earliest definitions by Schumpeter in describing the process of “creative destruction” (Schumpeter, 1934). Freeman and Engel suggest innovation “begins with a novel idea and concludes with market introduction” (Freeman & Engel, 2007). However, innovation is perhaps seen best as a process, per (Trott, 2008; Fitzgerald, Wankerl & Schramm, 2011; Godin, 2006):

\[\text{Idea} \rightarrow \text{development} \rightarrow \text{manufacturing} \rightarrow \text{product} \rightarrow \text{commercial market}\]

Innovation, according to this process, may appear linear and static, but as shall become clear, innovation as a process is dynamic (Fri, 2003). Successful innovation requires continuous iteration to ensure that technology development in the near-term is aligned with a commercial interest in the long-term, with the understanding that not all technologies or inventions ultimately yield viable products desired by the market (Fitzgerald, Wankerl & Schramm, 2011; Pisano, 2015; Teece, 2010a). One common misinterpretation of innovation is that novel technology is itself an innovation, i.e. a physical artefact. However, technology by itself, as well as new knowledge or scientific understanding, does not constitute nor guarantee innovation (see (Trott, 2008; Schumpeter, 1934; Park, 2005))\(^\text{10}\).

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\(^\text{10}\) An important definition also relates to the definition of technology. Technology is often synonymous with hard science and engineering (Gallagher, Holdren & Sagar, 2006). Brooks defines technology as being hardware, software, practices, as well as embodied knowledge that results in effective practical use (Brooks, 1967). As such, the processes and infrastructure that enable application of “hard” science and engineering, i.e. the “soft” aspects, can also be subject to innovation (Phaal, Farrukh & Probert, 2010; European Industrial Research Management Association (EIRMA), 1997).
Simply, in this thesis, innovation is defined as: “invention plus exploitation”\textsuperscript{11}, where an invention is the development of new technology, product or process; and exploitation is the identification of a commercial use for that invention (Godin, 2006).

2.2.2. Innovation models

Innovation models are conceptual frameworks that describe how innovation occurs by mapping the interactions between the components of the innovation process (e.g. technology, market) (Bonvillian & Weiss, 2015). Over time, innovation models have evolved in complexity. The historical progression of innovation models has been interpreted slightly differently in several recent publications, specifically (Godin, 2006; Bonvillian & Weiss, 2015; Rothwell, 1994; Taferner, 2017; Galanakis, 2006). The following analysis represents a new interpretation where innovation models are presented as four distinct generations.

2.2.2.1. First-generation: linear innovation

Economic progress combined with several new technology breakthroughs in the post-war era (the 1940s) led to the belief that successful innovation, i.e. successful products in the market, was due to more and better R&D (Rothwell, 1994). Often associated with Director of the U.S. Office of Scientific Research and Development Vannevar Bush\textsuperscript{12} (see (Bush, 1945)), the model perceives innovation as something of a direct progression from scientific discovery to products which will then turn a profit in the market (Rothwell, 1994; Godin, 2006). This model, emphasising R&D, is now known as the linear model (or pipeline model) of innovation (Hannola, Friman & Niemimuukko, 2013; Bonvillian & Weiss, 2015). As a “technology-push” model, the linear model is driven by scientific research, know-how and a “push” for the resulting technology to be deployed in the market, see Figure 2-1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{linear_model.png}
\caption{Linear innovation model, adapted from (Rothwell, 1994; Gallagher, Holdren & Sagar, 2006; Taferner, 2017).}
\end{figure}

\textsuperscript{11} With thanks to Dr Robert Phaal for developing this definition.

\textsuperscript{12} Although Vannevar Bush is often credited with creating the linear model, the precise source of the model remains nebulous. Although Bush talked about causal links between scientific research and socioeconomic progress, Godin contends that economists and business schools are responsible for extending the model (Godin, 2006).
2.2.2.2. **Second-generation: induced innovation**

The *linear model* has prevailed in public science laboratories where the risk associated with new ideas in expensive or complex science, often relating to “hard” technologies and transformational breakthroughs, can be taken on by governments (as detailed in 2.3) (Godin, 2006; Bonvillian & Weiss, 2015). However, owing to economic conditions in the 1960s, when it was realised that technology and products are merely a means to an end to satisfy market (or customer) needs, the “market-pull” or *induced innovation* model was developed (Rothwell & Soete, 1983). In the *linear model*, it is assumed that markets will emerge (or evolve, in the case of existing markets) to adopt a novel technology, and it is normal and acceptable that there is a lengthy period to get that technology from laboratory to market (Hannola, Friman & Niemimuukko, 2013; Brem & Voigt, 2009). In the *induced innovation* model, the opposite is assumed. Driven by growth and market share, companies sought to place emphasis on understanding and then stimulating market demand (Rothwell, 1994; Schmookler, 1966; Godin, 2006). As such, technology was seen as having “reactive” role whereby if there was market demand, R&D would yield a new product (Rothwell, 1994), see Figure 2-2.

![Figure 2-2 Induced innovation model, adapted from (Rothwell, 1994; Taferner, 2017).](image)

The induced model is typically exploited by the private sector where market opportunities are identified, and technology developed to meet demand quickly; to establish market control. With expediency and cost in mind, incremental technologies are preferred over complex, disruptive ones\(^\text{13}\) (Bonvillian & Weiss, 2015). The induced model is, therefore, limited in situations where technology solutions cannot be developed simply or quickly to meet certain market demands. Technology developed on the *induced innovation* model must match the technical performance and cost versus the incumbent technology in the market, or else it may be rejected by the market. Typically, then, *induced innovation* is not suited to developing complex technologies such as space technology; a sector that places

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\(^{13}\) Incremental innovation is the process by which technology is improved gradually over time. Examples of incremental innovation are the solar cell or energy efficiency improvements in thermal power cycles, see (Kline & Rosenberg, 1986) and Figure 15.7 in (Nuttall, Clarke & Glowacki, 2012) respectively. By contrast, disruptive innovation occurs when new technologies, or new combinations of existing technologies, drastically change the way a market or industry functions (Kostoff, Boylan & Simons, 2004). An example of disruptive innovation is the internet (Bonvillian & Weiss, 2015).
high-tech technology at the centre of its product development and has – importantly – traditionally been developed via the *linear model* (Park, 2005). The *induced innovation* model is, therefore, better suited to private industry which tends to be risk-averse, i.e. it only adopts technology that does not require substantial financial investment or time, instead opting for technology which is “market-ready” (Hayes & Abernathy, 1980; Bonvillian & Weiss, 2015). In consequence and by necessity, therefore, the longer-term outlook required for complex technology R&D and disruptive innovation typically means that it falls to the public sector to be developed on a *linear model*.

### 2.2.2.3. Third-generation: coupling and manufacturing-led models

In the 1980s amidst two major oil crises and consequential market saturation with little uptake of new products, there was a need to re-think the *induced innovation* model. There was a realisation that coupling the two existing innovation models, accounting for both the technology-push and market-pull effects, could yield a more effective model. As such, various coupling models were developed to identify market gaps that presented opportunities for R&D, recognising the simultaneous influence of technology development and market needs. The *coupling* model represented a shift to the first innovation model that was considered dynamic. The formerly disparate stages of innovation, although still functionally distinct, now interacted in an interdependent and complex system with various feedbacks (Kline & Rosenberg, 1986; Rothwell, 1994; Hannola, Friman & Niemimuukko, 2013; Galanakis, 2006). Figure 2-3 shows Rothwell’s coupling model (Rothwell, 1994), which simply highlights the stages of the innovation process and its connectedness. Figure 2-4 shows Kline and Rosenberg’s more complex but more comprehensive chain-linked model (Kline & Rosenberg, 1986), which shows how the feedback loops at all stages of the innovation process influence each other. In particular, both models show the explicit technology-push and market-pull functioning together at all stages of the innovation process\(^{14}\).

\(^{14}\) Also see Cooper’s *stage-gate* model for product development (Cooper, 2008).
At the same time as the emergence of coupling models, a separate innovation model was derived largely from observation of the manufacturing successes of the Japanese automotive and electronics industries (Galanakis, 2006). The so-called *manufacturing-led innovation* model considered all stages of the innovation process to progress in parallel (Bonvillian & Weiss, 2015). Most important was the emphasis on hardware; that challenges during the production stage can be tackled through prototyping, providing a real-world demonstration of the feedback loop between technology development and market demand. The *manufacturing-led* model allowed problems as well as inefficiencies to be eked out.

\[\text{Figure 2-3} \quad \text{Coupling innovation model, in (Rothwell, 1994) but graphic reproduced with permission from (Galanakis, 2006).}\]

\[\text{Figure 2-4} \quad \text{Chain-linked innovation model, reproduced under a Creative Commons license from (Kline & Rosenberg, 1986).}\]

\[15^\text{The German automotive industry also adopts a *manufacturing-led innovation* model; together with Japan it dominates the global automotive industry, see (Bonvillian & Weiss, 2015).}\]
during the development process\textsuperscript{16}, smoothing the route to market (Imai, Nonaka & Takeuchi, 1985; Galanakis, 2006; Bonvillian & Weiss, 2015; Rothwell, 1994). A representation of the \textit{manufacturing-led} model is shown in Figure 2-5.

![Figure 2-5 Manufacturing-led “parallel development” innovation model, originally by (Rothwell, 1994) but graphic reproduced with permission from (Galanakis, 2006).](image)

\textbf{2.2.2.4. Fourth-generation and beyond: systems models}

Until around the mid-1990s, successful innovation was often interpreted as “closed”, with inventions developed within the boundaries of individual organisations necessary for competitive advantage\textsuperscript{17,18} (Galanakis, 2006). Previous models identified the importance of feedback; that the research stages of the innovation process are only useful if the back-end connections are in place. However, a new focus on the network effects, i.e. obtaining support from other actors in the innovation system led to what is here defined as the \textit{systems innovation model} (Brem & Voigt, 2009; Bonvillian & Weiss, 2015).

Since their conception, developments in \textit{systems models} have further emphasised \textit{systems thinking} and network effects in an attempt to capture the complexity of overlapping interactions among actors within innovation systems (Taferner, 2017; Galanakis, 2006; Gallagher, Holdren & Sagar, 2006). An example of a \textit{systems model} is the \textit{Triple Helix} model, which links universities, industry and government (see (Etzkowitz & Leydesdorff, 1995)). However, the \textit{innovation organisation} model – see (Bonvillian & Weiss, 2015) – is

\textsuperscript{16} The \textit{manufacturing-led} model was used principally by Toyota in Japan, see (Liker, 2004). The importance of Toyota’s manufacturing-led lean innovation approach is detailed in 2.5.5.

\textsuperscript{17} Open innovation is discussed in 2.5.6.

\textsuperscript{18} There are, of course, examples to the contrary, see (Bonvillian & Weiss, 2015).
identified as an example of a recent systems model most relevant for fusion, which is discussed in 2.5.1.

2.2.3. **On the use of the term “systems” as engineering systems**

Before moving on, the use of the terms “system” and “systems thinking”, both referred to in the preceding section, need to be understood. These terms must be explored in the context in which they are used in this thesis. The term “system” has several definitions, and it has evolved differently in several academic and practical environments\(^\text{19}\) (Mindell, 2002). All descriptions share an understanding that a “system” is anything that involves the complex interaction of multiple parts, where those parts are taken together, rather than separately.

However, the use of “system” in this thesis is based on the approach to studying *engineering systems*, as developed by the division of the same name at Massachusetts Institute of Technology (MIT). *Engineering systems* approaches attempt to understand how disparate elements of a complex technology system can be integrated. However, it is not concerned only with technology development, as in *systems engineering*\(^\text{20}\). Instead, it is concerned with the interrelations between the physical and social (non-human and human) dimensions, and thus blurs “the boundaries between machine operation and human organization, between engineering and management” (Mindell, 2002). MIT engineering systems division defines *engineering systems* as the study of “the underlying principles and methods for designing complex socio-technical systems that involve a mix of architecture, technologies, organizations, policy issues and complex networked operations” (Department of Aeronautics and Astronautics (Massachusetts Institute of Technology), n.d.)\(^\text{21}\). As well

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\(^\text{19}\) Mindell usefully reviews the definition of “systems”, including to the way in which it is used to describe a philosophical construct, e.g. a political paradigm (a “one-party system”) or in the context of warfare (“command systems”) (Mindell, 2002).

\(^\text{20}\) Quite confusingly, “engineering systems” is not a synonym for “systems engineering”. Whilst some literature uses both interchangeably, this thesis defers to the delineation by Murman and Allen, whereby “systems engineering” describes the technical dynamics and the internal organisation of those technical dynamics, and not the broader environment in which technology is developed, e.g. social, commercial drivers etc. Systems engineering, for instance, could be used to describe tritium breeding blankets as a technology (Murman & Allen, 2003).

\(^\text{21}\) Simon Ramo, a pioneer in *engineering systems*, provides a definition with a stronger link to the broader definition of “systems”, stating that it is “a branch of engineering which concentrates on the design and application of the whole as distinct from the parts, looking at a problem in its entirety, taking account of all the facets and all the variables and linking the social to the technological” (Hambleton, 2005).
as the technological elements, *engineering systems* approaches acknowledge and account for the environment – the processes (e.g. R&D, manufacturing), drivers (e.g. economic, social and environmental), and actors (e.g. organisations, people, governments) – in which that technology is being developed (Mindell, 2002; Murman & Allen, 2003).

*Systems thinking* is about seeing “the bigger picture” to understand the connectedness between elements of a system (The Systems Practice Team (The Open University), 2005). Whilst there are clear overlaps, *systems thinking* research has a broader scope than – and different focal point to – *engineering systems*22. *Systems thinking* seeks to understand the behaviour and dynamics of complex systems (Sterman, 2000). Simply, where *engineering systems* is concerned with determining “how”, *systems thinking* is concerned with determining “why”. Both methods are useful, and to some extent, complementary. Both facilitate understanding and can be used to drive change in systems. The term *systems thinking* is not used in this thesis but is discussed here to separate it from *engineering systems* research.

2.3. **The public fusion programme and the linear model of innovation**

As detailed in 2.2.2.1, the *linear model* typically underpins government-led projects in order to guide the early stages of innovation that carry high cost and the most technological risk. A variation of the *linear model* is the *extended linear model* (commonly known as the *extended pipeline model*) which sees government involved until the latter stages of the innovation process to cross the so-called “Valley of Death”, see (Lopes-Cardozo, 2019; Branscomb & Auerswald, 2002; Evans, 2002). The valley of death represents the innovation gap between technology and prototypical product when there is still a significant risk of failure but a clear route to a commercial product that is suitable for private industry – which is more financially conservative, risk-averse, and short-term in its outlook – to take to market. The extended pipeline model avoids one of the shortfalls of the standard *linear model* in that it enables technologies of high perceived technological and societal need, but which have a substantial barrier to entry, e.g. high cost or market risk (Gallagher, Holdren & Sagar, 2006). Hence, it was behind some of the great disruptive technologies of the 20th century, for example, computing, space exploration, biotechnology and nuclear fission power (Bonvillian & Weiss, 2015; Ruttan, -2006; Lopes-Cardozo, 2019).

The conventional view as to why fusion has not yet been “cracked”, let alone commercialised, is that it is amongst the most difficult scientific challenges humankind has

22 The most obvious link is that in both engineering systems and systems thinking research, systems are viewed as a complex and interdependent network, where “you can’t just do one thing” without considering the impact on other parts of the system.
ever faced. It is simple to say that it is the scale of the technical challenge that has caused the setbacks, delays and cost overruns. Whilst this argument appears compelling, why, then, have so many other advanced technologies – which also seemed to be insurmountable beforehand – successfully commercialised on the same linear model? And why then, can such a model not still be successful for fusion in the future? There are several key weaknesses and limitations of the linear model, which are, in fact, best understood via analysis of its previous successes. Perhaps most apt is the example of nuclear fission technology.

At the dawn of the nuclear age in the 1950s, the only model of innovation to develop technology was the linear model. In other words, because of the scale and cost – but also the strategic importance of nuclear fission as a weapons technology – government laboratories had a unique capability to undertake development. Harnessing energy from the fission reaction is relatively straightforward, and it only took a short period before it was possible for private companies to take on the development and the commercialisation of fission power. When the commercial potential for fission technology was established, it was quickly moved into private companies to commercialise it, and nuclear laboratories subsequently moved to become the R&D partner to support the nuclear industry, but not to develop commercial technology.

Fusion ostensibly represents a greater technical challenge, which must be overcome in order to thereafter show its commercial potential. However, over half a century later and fusion is still the subject of publicly-funded programmes based on out of government laboratories, still operating on a linear model. The continued adherence of fusion to the linear model is evident in efforts to design next-step DEMO machines that will follow ITER, but which will not come into operation until around 2050, i.e. planning for the “development” step of the innovation process. DEMO, a collective term in the fusion community to describe the prototypical power plant, will extrapolate from ITER’s technical basis resulting in an even larger tokamak, only with greater energy output and more advanced technologies. DEMO, in the context of the linear model, represents the device that will prove the technology can be commercially viable. Importantly, current efforts envisage that DEMO will be publicly funded, which is further proof that fusion development via the public programme is specifically operating on an extended linear model. Unlike ITER, for which the cost burden is shared, there are multiple DEMOs under development around the world as domestic programmes\(^{23}\), as shown in Figure 2-6.

\(^{23}\) The rationale for multiple DEMO programmes is in part due to divergence regarding the optimal technical concept, e.g. the United Kingdom is currently considering the spherical tokamak approach
As a government-led project that has consumed a substantial portion of global fusion R&D resource over the past two decades, ITER has limited the development of alternative approaches and effectively “placed all of fusion’s eggs in one basket” (Walker & Haines, 1997). Accordingly, the success of such a project is paramount. Incentives and pressures lead to an avoidance of risk by, for example, only permitting the use of mature technologies. Risk minimization and avoidance leads to more rigorous designing and testing, which in turn creates delays and cost overruns. The rationale is that over time, the technology will be better understood, and the chance of success improved; ergo, risk will be reduced. However, in extremis, this cycle proliferates, and the notion of “failure is not an option” dominates (McCurdy, 2001). For ITER, this approach has culminated in a focus on rigorous planning and testing to reduce risk before building, which has increased cost and led to delays (Lopes Cardozo, Lange & Kramer, 2016; Lopes-Cardozo, 2019; Locatelli, 2017). For publicly funded government-led fusion programmes in general, this has resulted in the pursuit of devices that are not well suited for commercial application and unlikely to be developed fast enough to contribute to the energy mix until at least the latter half of the 21st century (Lopes-Cardozo, 2019). Similar problems have previously manifested in other

(see (Chapman, 2019)). However, it may also be due to protectionism, i.e. each nation wants to be the first to demonstrate a reactor that scales to market.
large-scale government-funded projects such as NASA’s space programmes, see (McCurdy, 2001) and section 5.5 in (National Academies of Sciences; Engineering; and Medicine, 2018).

Thus, development on the *linear model* commonly yields products that may be technologically advanced, but which are not necessarily commercially viable. If placing an overarching focus on the technical performance, and cost considerations are omitted, then, broadly speaking, it is possible to devise a large number of solutions to any given technical problem (Kline & Rosenberg, 1986). The *linear model* perpetuates the view that technology development occurs in “a sort of R&D vacuum, without any input until a fortuitous discovery or invention is made; then market and implementation are explored later” (Fitzgerald, Wankerl & Schramm, 2011). It commonly yields inventions for which the commercial application is not understood. History indicates that dependence and predication on a technology-push approach can prove disastrous for commercial success; the development of a marvellous invention alone rarely leads to commercial success (Kline & Rosenberg, 1986; Granstrand, 1998; Park, 2005). In other words, unless an invention reduces the cost, or substantially increases performance or provides some larger societal benefit at a marginally higher cost, then it is unlikely to be valued in the market and will likely result in commercial failure (Pisano, 2015; Gallagher, Holdren & Sagar, 2006)\(^2\). A typical example of this is the development of Concorde, which – whilst arguably an engineering masterpiece – was a significant commercial failure\(^2\) (Kline & Rosenberg, 1986). Furthermore, even when the technical feasibility of that new technology has been demonstrated, and cost becomes competitive, it still may not compete in the market with already established technologies, principally because of barriers relating to market organization, infrastructure, regulations, slow capital stock turnover or public perception, see (Gallagher, Holdren & Sagar, 2006). Solar energy provides a prescient example here, as the technology has evolved and reduced in cost, yet its impact on global electricity (and energy) supply is negligible, see (Philipps et al., 2015).

\(^{24}\) It must be recognised that the same is true of the opposite approach, i.e. that market-driven performance requirements for a product that is not technically feasible can also result in overall innovation failure. Furthermore, the upper limits of perceived technological feasibility do not present insurmountable barriers. Scientific progress often works to overcome these barriers, but this can be slow through continuous scientific and development efforts, see examples in (Kline & Rosenberg, 1986; Bonvillian & Weiss, 2015).

\(^{25}\) The word ‘arguably’ is used to describe the engineering excellence of Concorde as serious safety weaknesses of the aircraft were revealed by the tragic crash of an Air France Concorde near Paris on the 25\(^{th}\) of July 2000.
Fusion energy has long been sold as having the potential to be superior to any competing energy technology. Sanchez suggests that after demonstrating net electricity generation, DEMO will result in an influx of private investment to construct the first commercial power plants, leading to a “relatively fast development, leading to a significant share of fusion in the energy mix during the second half of the century” (Sánchez, 2014). Beyond the fact that even the earliest milestones (net power gain) that will demonstrate the potential of fusion power have not yet been achieved, it is dangerous to suggest that the technological sophistication will be intrinsically valued in the market; not unless fusion offers superior performance at marginal extra cost (Kline & Rosenberg, 1986; Walker & Haines, 1997). Projections routinely suggest that the cost of electricity for fusion is competitive with large fission power plants, despite the fact that DEMO-type fusion power plants are expected to be significantly more complex than fission power plants, see (Ward, 2007; Walker & Haines, 1997).

In summary, the primary reason that the linear model has prevailed in fusion is that the private sector is waiting for a certain level of development and a reduction in risk to be attained before investing. This highlights perhaps the greatest weakness of the linear model: that it is overly simplistic, and distorts the dynamics required in a successful innovation process, principally because it places the minimal emphasis on commercial requirements that in fact drive technology development (Fitzgerald, Wankerl & Schramm, 2011; Bonvillian & Weiss, 2015). It is imperative to understand the shortfalls of the linear model, and thus the public fusion programme as an alternative model of innovation that accounts for those shortfalls can be adopted by fusion start-ups so that they can advance more effectively towards commercialisation. Fusion start-ups can instead seek an approach that addresses the engineering and commercial issues in parallel, noting that the logic even if all technical issues are solved on ITER or even on a subsequent DEMO, this does not necessarily mean it will scale to a commercial fusion power plant that will succeed in the market. Secondly, and relatedly, they can proceed with an understanding of the importance of keeping complexity as low as possible with commercialisation (low-cost, high-performance) as the end-goal in mind.

26 It is not suggested that the public fusion programme has adopted, or continues to adopt, a linear model of innovation intentionally. On the contrary, this thesis contends that it was not planned, largely unavoidable, and in many instances necessary.
2.4. Fusion start-ups: a paradigm shift

2.4.1. The emergence of fusion start-ups

Frustration over delays in the ITER project; a belief that fusion scientists had doubled down on a single technical approach (the tokamak) too early; and the advent of new technologies has spurred scientists and entrepreneurs into pursuing ideas that may provide an alternative pathway to fusion. Since the early 2000s, a significant number of entrepreneur-led and private investor-funded fusion start-ups have been established. Some fusion start-ups are seeking to incorporate disruptive technologies into concepts with a well-established physics base, such as tokamaks incorporating high-temperature (HTS) magnets (see (Sykes et al., 2015; Sorbom et al., 2015)). Others are seeking a route to fusion by a wide range of either wholly novel fusion reactor concepts, i.e. not based on the tokamak (see (Wurden et al., 2016; Clery, 2019)). However, all fusion start-ups are taking an approach that hinges upon the promise of a disruptive technology or disruptive (i.e. unexplored) plasma physics. Examples of well-established fusion start-ups, with key information on the technical approach, are shown in Table 2-1.

<table>
<thead>
<tr>
<th>Fusion start-up</th>
<th>Concept</th>
<th>Key disruptive technologies</th>
<th>Launch date and estimated investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commonwealth Fusion Systems (USA)</td>
<td>Conventional tokamak</td>
<td>HTS Magnets</td>
<td>2018; $114M</td>
</tr>
<tr>
<td>(Sorbom et al., 2015)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Light Fusion (UK) (First Light</td>
<td>High-velocity capsule</td>
<td>Gas gun for projectiles at hypervelocity</td>
<td>2011; $40M</td>
</tr>
<tr>
<td>Fusion, n.d.)</td>
<td>implosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Fusion (Canada) (Laberge,</td>
<td>Acoustic compression</td>
<td>Driver for plasma compression</td>
<td>2002; $200M</td>
</tr>
<tr>
<td>2016)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helion Energy (USA) (Helion Energy, n.d.)</td>
<td>Field Reverse Configuration</td>
<td>Particle accelerator (plasma liner)</td>
<td>2013; $45M</td>
</tr>
<tr>
<td>TAE Technologies (formerly Tri-Alpha</td>
<td>Field Reverse Configuration</td>
<td>Particle accelerator (plasma liner)</td>
<td>2001; $700M</td>
</tr>
<tr>
<td>Energy) (TAE Technologies, n.d.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokamak Energy (Sykes et al., 2015)</td>
<td>Spherical tokamak</td>
<td>HTS Magnets</td>
<td>2009; $150M</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 2-1 List of fusion start-ups (determined by amount invested, in alphabetical order, estimated based on published financial data, January 2020).
Aside from the technical approach utilising disruptive technologies, fusion start-ups are founded on the notion that the lack of incentive for private money and the “early awareness of what will be required in an eventual real-world application” is a key barrier to progress (Kaslow et al., 1994). All start-ups envisage ambitious programmes that – if realised – will accelerate the process of commercialisation, and all are via smaller, simpler and cheaper devices (Costley, Hugill & Buxton, 2015; Whyte et al., 2016; Wurden et al., 2016). Led by entrepreneurs and backed by investors, both of whom have an appetite for risk, fusion start-ups are taking an opportunity to use venture capital to get to fusion faster by accepting conditions of uncertainty and risk in their mission to develop commercial fusion (see (Freeman & Engel, 2007; Rothrock, 2016; Baron, 1998)).

Fusion start-ups must ultimately generate a return on investment for their backers. As such, predicated explicitly on successful commercialisation, fusion start-ups are predicated upon a fundamentally different to the approach of the public programme, and in fact, operate on a different model of innovation.

2.4.2. The fusion start-up approach to innovation

Unlike public efforts, based strongly in developing scientific understanding before moving to the next step, fusion start-ups are founded on the notion that building just enough confidence in the science enables a move to engineering; where then the science will follow (Fitzgerald, Wankerl & Schramm, 2011). The initial step in most inventions comes from designing and testing an idea; not from the science (Kline & Rosenberg, 1986). An accelerated route to convert science into technology is possible if information about the science exists and is readily available to exploit, i.e. there is a need for the technology to be developed (Zurcher & Kostoff, 1997). As such, fusion products based on disruptive technologies can provide dramatic improvements to the established public programme paradigm, which – historically – has initiated new products or even industries in other sectors (Kostoff, Boylan & Simons, 2004). Moreover, whilst large organisations, in this case, the public fusion programme, may have an abundance of expertise and access to the latest technology, they are not always well positioned to recognise or to capitalise on opportunities for commercialisation. Successful technological advancement has historically come from competitive environments, including – quite typically – by the emergence of disruptive start-ups, per (Klevorick et al., 1995; Schumpeter, 1934; Park, 2005). Therefore, fusion start-ups have the opportunity to disrupt despite their lack of pedigree and size.

As characterised in 2.3, thus far public fusion programmes have mainly followed a linear model of innovation in which science and technology are the primary focus and commercialisation plays only a minor role in the early stages of innovation. Fusion start-ups are, by contrast, backed by investors who want to see rapid development towards a
commercial product as well as a return on investment (ROI). Intrinsically, therefore, fusion start-ups must innovate with a continuous focus on commercial requirements. This necessitates that technology development is continuously adapted towards what is likely to be commercially viable, rather than only what is technically possible. Naturally, and over time, technology R&D will prove whether an invention is technically feasible. However, limited resources, and in some cases an incomplete understanding of the core science and only partially developed technology, means that start-ups and their backers are prepared to accept higher risk in pursuing those inventions that may later fail. Of particular importance, therefore, is the different attitude to risk. Although investors may accept the lengthy timescales to which they will see an ROI\(^{27}\) – and even the potential risk that they will not see an ROI at all – they avoid overly cautious decision-making (Baron, 1998; Rothrock, 2016). Therefore, fusion start-ups proceed with an attitude to risk that is not primarily based on strategies of minimization and avoidance, but rather the focus is on a need to maintain momentum, to expect problems and to learn from them quickly, see (McCurdy, 2001). By rapidly learning and adapting from failures, fusion start-ups can be expected – fundamental science permitting – to make significant progress measured in the order of years rather than decades. With this higher acceptability for risk, in conjunction with smaller and simpler reactor concepts\(^{28}\), fusion start-ups have the potential to develop technology at higher speed and lower cost. Accordingly, the underlying philosophy of fusion start-ups to iterate rapidly, to proceed with risk and to learn from failure, indicates that they operate on a fundamentally different model of innovation. Ostensibly, a paradigm shift towards fusion start-ups, developing via an alternative model of innovation is underway.

2.4.3. A paradigm shift in fusion

A paradigm is underpinned by universally recognised scientific achievements in a particular research area or industry which, for a time, provide a model for practice and procedure in the pursuit of new solutions (Bonvillian & Weiss, 2015). The definition of paradigm shift is taken from Kuhn as \textit{“the world view underlying the theories and methodology of a particular scientific subject”} (Kuhn, 1962). Bonvillian and Weiss contend that paradigms that have

\(^{27}\) Of noteworthy reference is the company Reaction Engines Ltd, a similarly hi-tech and hardware-focused engineering company developing an air-breathing rocket engine. Reaction Engines Ltd was established in 1989 but has not yet realised its vision. Its initial investors are – presumably – still waiting on an ROI, yet the company has continually secured private investment. Reaction Engines provides pedigree for fusion start-ups that long-term investment is plausible.

\(^{28}\) For clarity, \textit{“smaller and simpler”} here relates to the cost and complexity of fusion reactors, rather than necessarily the physical size; something that is large but simple is not necessarily high cost.
existed for lengthy periods of time are “legacy sectors”; a sector that is entrenched in a particular way of thinking or operation that is difficult to displace (Bonvillian & Weiss, 2015). Kemp et al. further describes a legacy sector as a set of prevailing technologies and ideas that have already benefited from all kinds of evolutionary improvements, in terms of costs and performance, and in terms of accumulated knowledge, investment of time, infrastructure, the skills of workers, production routines, regulations, and culture (Kemp, 1994; Hekkert et al., 2007). The incumbent fusion programmes are here considered a legacy sector. Specifically, it is defined as such because (compiled from definitions in (Bonvillian & Weiss, 2015)):

- Large tokamaks receive the majority of funding and R&D support (the majority of effort and focus has been placed on a single route to fusion via ITER\textsuperscript{29}, and critical supporting technologies, e.g. divertors).
- There is an established government infrastructure and architecture which discourages and/or cannot support new entrants.
- Educational and professional institutions are geared to support R&D into large tokamaks and have thus trained a generation of experts on tokamaks. The result is that all supporting satellite R&D is focused on established technology.
- Powerful “vested” interests support the project, i.e. governments and – by virtue – the general public. Public money has supported the large tokamak approach, and thus for political reasons, it must succeed.
- The innovation time horizon is longer than conventional private financing structures can support, i.e. the lengthy return on any investment (as well as the high risk for the early-stage technology) is not conducive to private investment.

In society in general, start-ups have grown to play a key role as disruptive innovators, especially to disrupt “legacy” sectors\textsuperscript{30}. However, whilst fusion start-ups are disruptive, they are not “competing” in the same way that other start-ups might. Instead, they are competing against a paradigm of existing technology and a way of doing things, i.e. the approach the innovation, which is well established. Existing technologies, i.e. large tokamaks, persist because even in the face of potential advantages of new technologies that may improve performance, they are supported by the existing infrastructure, and they represent the safer option (Kline & Rosenberg, 1986; Hekkert et al., 2007; Bonvillian & Weiss, 2015; Rosenberg, 1972). Legacy sectors can thus be described as entrenched. However, if the potential of the novel technology can be shown to transform novelty into practical or

\textsuperscript{29}Experiments on some other concepts are ongoing in parallel to ITER, but with comparably limited funding, e.g. the Wendelstein 7-X stellarator-type fusion reactor, see (Wolf et al., 2016).

\textsuperscript{30}An example of such an innovator is Uber, which is disrupting the existing taxi model.
commercial significance, then the introduction of that technology can result in creative
disruption (Kline & Rosenberg, 1986; Schumpeter, 1934). It is on this notion that fusion
start-ups are predicated.

Fusion start-ups are developing disruptive technology by following a fundamentally different
model of innovation that requires novel technologies, or concepts, to be developed quickly
towards an explicit commercial goal. In spite of the fact that fusion start-ups are at such an
early stage of development in which not even technical viability has been proven, and thus
all fusion start-ups inherently represent a high risk and long-term investment, they have
gained significant support from private investors to the tune of well over US$ 1 Billion
(estimate as of March 2020). This is highly unusual. It is also further evidence that fusion
start-ups are not operating on the linear model, in which private investment is typically made
only when the commercial potential of a technology has been demonstrated (see 2.2.2.1).
To understand more about the incumbent paradigm shift to fusion start-ups, it is instructive
to compare with the now well-established paradigm shift in the space exploration sector.

2.4.4. Paradigm shifts in the space sector

The hypothesis is that fusion start-ups are to publicly funded fusion programmes like
SpaceX, Blue Origin or Virgin Galactic are to governmental or intergovernmental space
agencies such as NASA or the ESA. The parallels in the innovation approach are clear.
Space start-ups such as SpaceX – as perhaps the most well-known example – are
companies backed by private venture disrupting a sector previously occupied only by
national laboratories. Where NASA’s mission is to advance the boundaries of technology
and science31, space sector start-ups were founded to commercialise space travel. ITER –
an experimental project – will answer key technical questions and pave the way for future
commercial development (via DEMO), whilst fusion start-ups are founded to realise and
exploit the technology’s commercial potential. Both technologies require substantial
investment, specifically for the development of expensive and complex hardware; both have
significant front-end risk, with many technology unknowns; and both have an almost unique
capacity to change the world. However, the specific focus on demonstration is perhaps
what is central to underpinning the success of space start-ups. SpaceX has actively
demonstrated the value of learning rapidly from failure through short innovation cycles; the
time taken from which to build, test and learn, via its series of Falcon rockets. As a result,
the “SpaceX model” is now being suggested as a foundation for the development of
advanced nuclear fission power, see (Bowen, 2019; Abdalla et al., 2019), and it also

31 See (NASA, n.d.).
underpins aspects of the U.S. ARPA-E (Advanced Research Projects Agency Energy) programme\textsuperscript{32,33}.

Moreover, as with SpaceX, throughout history, it has always been first demonstration – whether it be the first controlled powered flight or the first controlled fission reaction – that has, in hindsight, been considered as the breakthrough point. It is, therefore, also useful to take a historical perspective. In the case of controlled powered flight, the breakthrough demonstration was by the Wright brothers in December 1903. While controlled fusion has been achieved in the JET and TFTR tokamaks, see (Hawryluk \textit{et al.}, 1998; Keilhacker \textit{et al.}, 1999), the equivalent of the Wright brother’s first flight – net fusion power – has not yet been achieved. As before, ITER is not expected to achieve this until at least 2035, but many fusion start-ups are aiming to achieve it in the next few years. Whilst SpaceX knows that space travel is technically possible, fusion start-ups, by contrast, do not. As such, an important comparison with the Wright brothers can be drawn. Fusion start-ups are not only aiming to commercialise fusion on an accelerated timescale but also to be the first to demonstrate fusion’s breakthrough moment. Thus, rather than comparing the current position of fusion start-ups to SpaceX, it is more appropriate to like it to the position of NASA in the 1960s \textit{before} it successfully landed humans on the moon, to the Wright brothers in the early 1900s \textit{before} anybody had demonstrated controlled flight\textsuperscript{34,35}. Such missions required innovation in environments in which the science was not understood. The mission requirements drove technology development, and the technology was developed under the notion that “it’s not science becomes technology becomes products. It’s technology that gets science to come along behind it” (see (Fitzgerald, Wankerl & Schramm, 2011; Kline & Rosenberg, 1986)).

\textsuperscript{32} Incidentally, ARPA-E has a mission – the “ALPHA” programme – which supports early stage R&D for fusion start-ups.

\textsuperscript{33} ARPA-E was based on the success of the U.S. DARPA (Defense Advanced Research Projects Agency), an agency set up to explore cutting edge military technologies in an environment devoid of bureaucracy or regulation. Lockheed Martin – a privately owned U.S. defence company, has a dedicated “Skunkworks” branch for a similar purpose. Incidentally, Lockheed Martin’s Skunkworks team is currently developing a fusion reactor.

\textsuperscript{34} Another key example is a manned mission to Mars (another of Elon Musk’s ambitions – yet to be achieved).

\textsuperscript{35} It must also be acknowledged that innovation is often accelerated in times of War, which is explored in depth by Ruttan (Ruttan, 2006).
To begin to converge on the innovation approach of fusion start-ups, it is edifying to combine the commercially-driven SpaceX approach to innovation with the historical perspective, i.e. with and without explicit commercial motivation. Firstly, fusion start-ups are targeting a “Wright Brothers” moment, defined as the moment at which the proverbial “wheels are off the ground”, and the point at which the scientific endeavour is deemed possible. Such a moment for fusion is here contended to be the demonstration of controlled fusion with net power gain, whereby more power is produced by a fusion reaction than the power supplied to it\(^{36}\). Secondly – and perhaps more importantly – fusion start-ups are approaching this goal by building, testing and learning, i.e. innovation through demonstration, rather than from pure scientific understanding. The next section will explore these aspects in greater depth.

2.5. Characterising innovation in fusion start-ups

The previous sections of this chapter have explored the shift towards fusion start-ups, broadly outlining the overall approach to innovation. However, the specific approach, i.e. how fusion start-ups carry out innovation, must be characterised. It is noted that up until now, the majority of analysis has focused on describing the fusion start-up approach. In contrast, this section both describes and prescribes the innovation approach in fusion start-ups. In other words, it gives both an explanation of innovation approach already inherent in fusion start-ups, as well as providing details on the ways in which fusion start-ups can develop their innovation approach.

2.5.1. Towards a model of innovation: The Innovation Organisation model

As a technological undertaking, fusion is highly complex (see (Durney & Donnelly, 2015)). As detailed, the perceived need to focus on the technical challenge is a key reason why the linear model has prevailed in fusion development. The technical challenges are of complexity and a scale not faced by other technology start-ups, so even in fusion start-ups perhaps it is understandable that there is a focus on the front-end of the innovation process\(^{37}\). However, as in 2.2.2.3, for the invention to ultimately succeed in the market, commercial drivers must be accounted for; and a lack of commercial knowledge has been identified as being the contributing factor in firm failure (Kakati, 2003). A suitable model of

\(^{36}\) The demonstration of fusion power gain arguably occurred in the Ivy Mike thermonuclear bomb test. However, the fusion reaction was uncontrolled and not for commercial purpose. As such, the word “controlled” is significant.

\(^{37}\) See (Koen et al., 2001) for a description of “fuzzy” front-end innovation.
innovation must, therefore, allow for simultaneous consideration of both technology-push and commercial-pull factors (Tura, Hannola & Pynnönen, 2017; Teece, 2010a; Bonvillian & Weiss, 2015; Godin, 2006). Conceptualised by Bonvillian and Weiss, the innovation organisation model is an example of a systems model of innovation (Bonvillian & Weiss, 2015). The model builds upon the previous system and network innovation models, for example, the national innovation systems model developed by the OECD (Organisation for Economic Co-Operation and Development (OECD), 1997). Like the national innovation systems model, the innovation organisation model focuses explicitly on the complex set of relationships among actors in systems. Most importantly, however, the innovation organisation model is focused on providing a model for innovation in legacy sectors. As such, the innovation organisation model is predicated upon fundamental ideas and principles principally derived from Schumpeter, in that disruptive innovation is central to economic advancement in the process of creative disruption; and from Christensen, in that established sectors can only be disrupted by radical inventions or products (Schumpeter, 1934; Christensen, 1997). The model, therefore, ties together the radical technology innovation that typically comes from the technology-push models and the incremental innovation that comes from market-pull models, thus sitting “at the intersection of invention and insight” (Kline & Rosenberg, 1986; Bonvillian & Weiss, 2015; Ruttan, 2001). Fusion, earlier defined as a legacy sector (see 2.4.3), requires disruptive innovation and thus, the innovation organisation model presents a basis for fusion start-ups.

### 2.5.2. Beyond innovation models: agile, lean and open innovation

Whilst the innovation organisation model provides a basis for understanding fusion development, in and of itself it does not provide an understanding of the specific technology development approach of fusion start-ups, i.e. the way in which start-ups “do” innovation. The underpinning philosophy of fusion start-ups is to build and test technology from which to fail and subsequently learn, whilst considering drivers from all stages of the innovation process. The iterative approach to technology development in particular means that fusion start-ups are already well aligned with start-ups from other similar sectors (see 2.4.4), and are fundamentally different from existing governmental fusion programmes. Moreover, the specific approach means that fusion start-ups are closely aligned with the well-established principles of agile, lean, and open innovation. Exploring fusion development in these contexts will provide a basis for the practical side of development, i.e. how start-ups “do” innovation, which will complement the innovation theory detailed thus far in this chapter.
2.5.3. The co-evolution of agile and lean innovation

To characterise and contextualise how fusion start-ups encompass aspects of agile, lean and open innovation, the key principles of each must be understood. Firstly, however, the origins and co-evolution of agile and lean must be disentangled.

**Lean innovation** has early roots in manufacturing. Its origins can be traced back to Deming’s process of “plan-do-check-act” for continuous product improvement from the early 1950s (Neave, 1987). However, Deming’s approach became well-known following the conceptual creation of the *Toyota Production System* (TPS) in the early 1980s, which are derived from Deming’s “14 points for total product quality management” (see (Neave, 1987; Liker, 2004)). Although developed and commonly known now as the underpinning principles for just-in-time manufacturing, the Toyota Production System provides important inferences for successful innovation. Then known as “lean production”, the approach emphasised the reporting of failure and learning from it, not minimising and avoiding the reporting of failure. It was also predicated on the perceived need to minimise waste in terms of time, resource and effort. The approach was extended from production methods to programme management and development, and hence *lean innovation* developed, see (Sehested & Sonnenberg, 2010). Agile innovation, by contrast, originated much later – in the early 2000s – to facilitate rapid development in software, see (Abrahamsson *et al.*, 2002; Beck *et al.*, 2001; Rigby, Sutherland & Noble, 2018). Agile innovation is specifically angled towards technology-to-market strategies, as it emphasises the speed of development via iteration through building, testing and learning to accelerate the process of innovation towards commercialisation (Ries, 2011). Despite distinct origins, more recently in much of the innovation literature agile and lean are often considered as synonymous38. In the modern context, therefore, both agile and lean have – to an extent – co-evolved as two distinct, but complementary and intertwined methodologies. Principally, although they come from different contextual settings both promote learning through discovery. A simple interpretation of this co-evolution is shown in Figure 2-7.

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38 In particular, see (Ries, 2011) in which “lean start-ups” are described as “agile”, and (Poppendieck & Poppendieck, 2003) where it is suggested that when put into practice lean principles can be agile tools.
For this analysis to the fusion context, agile and lean are separated, but inherent links mean that examples from both individual agile and lean literature, and the combined literature, are examined. Subsequently, open innovation – as a relevant but distinctly different from agile and lean – is also applied to the fusion context.

2.5.4. Agile innovation

2.5.4.1. Principles of agile innovation

Agile innovation is an approach based on the notion that taking an iterative approach to complex technology development will enable rapid progress in fast-moving and ever-changing environments, see (Tura, Hannola & Pynnönen, 2017). Agile innovation is a process often mistaken as a way of “doing things as usual, only faster” (Rigby, Sutherland & Takeuchi, 2016). Agile is not all about speed. Rather, it is about the concept of flexibility and adaptability to change requirements late on, i.e. the speed of getting to a product, even if imperfect (Abrahamsson et al., 2002; Gonzalez, 2014). The agile approach is also about developing the right technology for the right markets, which – via iterative development – facilitates effective and rapid innovation. The list below details the principles of agile
innovation compiled from (Miller & Lee, 2001; Ambler, 2002; Highsmith & Cockburn, 2001; Rigby, Sutherland & Noble, 2018):

1. Focus on fast delivery over shorter timescales on iterative cycles.
2. Regular product release using the most advanced technology (process, hardware, etc.) available, via “build-measure-learn” cycles towards a Minimum Viable Product (MVP). High speed necessitates simplicity.
3. Relating to (2); add complexity over time. Improve design iteratively and avoid unnecessary activities.
4. Test continuously for earlier and less costly changes, and thus lower risk; fail fast, learn fast.
5. Focus on building working product, rather than exhaustive plans and excessive documentation.
6. Focus on people as the primary drivers of project success. Nurture a creative and autonomous workforce with a collaborative and communicative working style that is responsive and adaptive to risks, and that embraces making changes to product and process (specifically see (Ifandoudas & Chapman, 2009))

2.5.4.2. Applying agile innovation to fusion

Agile can be applied via specific tools and methods, as described in (Tura, Hannola & Pynnönen, 2017; Hannola, Friman & Niemimuukko, 2013). However, it is the principles that underpin agile innovation that are more important here. Applying agile principles to fusion start-ups is not straightforward, due to the fact that agile has developed from software rather than hardware. More specifically, while agile has been applied to hardware, see (Rigby, Sutherland & Takeuchi, 2016), the development of fusion hardware is unlike, e.g. the electronics industry, which may take perhaps 1 to 2 years to develop a new technology. The application of agile to fusion thus requires an understanding that there is greater complexity and technological novelty, as well as a heavy focus on advanced materials, meaning that a specific piece of fusion hardware may instead take 5 to 10 years to develop. Even “low cost” in fusion is likely to be orders of magnitude higher than what is perceived as “low cost” in the electronics industry. This is, in fact, a key distinction. Fusion start-ups are focused on hardware-based technology development that necessitates – in the context of other industries adopting an agile approach – lengthy timescales between iterations and which are comparably high in cost. As such, it is about developing fusion technology that is as simple and as low-cost as possible, to facilitate “faster” timescales, i.e. accelerated development compared with the public fusion programme.

Agile innovation principles can be further interpreted to relate to fusion development in the following ways. Firstly, the challenges in fusion are complex and sometimes with
unknowns, meaning that engineering and design requirements change frequently based on the results of experiments or new market/customer needs. For effective innovation, there should instead be a focus on continuous development; typically, through experimentation. Fusion start-ups can, therefore, be agile if they focus on regular experiments, keeping the design of the “product” – in this case, a fusion reactor – as simple as possible, sticking to fundamental scientific principles whilst simultaneously using the most advanced technology available. Adopting the MVP concept; a version of a product that has the key features needed to demonstrate success, but that can be built with minimal effort and cost, fusion start-ups can develop on rapid cycles (Ries, 2011) (this notion is revisited in 2.6.3). Secondly, collaboration is fundamental due to the high complexity and uniqueness of many of the technologies present in a fusion reactor. Where possible, technology challenges can be broken into parallel development streams to again facilitate faster iterations. Each development stream can be managed by a workforce that is made up of highly skilled and creative specialists.

However, one important weakness relates again to hardware. Agile innovation appears ill-suited to problems where late changes could be expensive or could cause catastrophic technical failure, e.g. destroying a machine, thus compromising safety. Put simply; higher speed can result in lower quality. In engineering systems, pursuing low quality can lead to failures that result in accidents. Heeding this limitation, in particular for safety-critical technology systems39 – of which there are several in a fusion reactor – as long as caution is taken then an agile approach is still possible (similar challenges have been faced in the space sector, see (McCurdy, 2001)). Naturally and necessarily, though, safety will add time and cost to development that can be avoided in the application of agile to non-safety critical hardware-based industries.

2.5.5. Lean innovation

2.5.5.1. Principles of lean innovation

With its foundations to the manufacturing and the production stages of innovation, lean innovation has a different focal point to agile innovation which is more inherently focused

39 Much as “innovation” is often used to describe “an innovation” (see 2.2.1), the semantics of the word “system” are nuanced. In this instance, and elsewhere throughout this thesis, the term “systems” is used to describe a specific technology system, e.g. a tritium handling or tritium breeding blanket system, where there is no suitable alternative term.
on the development stage\textsuperscript{40}. Despite this, lean production has more recently been extended and evolved into lean innovation from production methods to programme management and development. In particular, lessons for \textit{lean development} are distilled from \textit{lean production} in (Poppendieck & Poppendieck, 2003)\textsuperscript{41,42}. The list below is based on (Poppendieck & Poppendieck, 2003), with contributions from (Agan, 2014; Liker, 2004; Schuh, Lenders & Hieber, 2011; Neave, 1987):

1. Reduce waste, where waste is anything that does not create value. Waste is thus characterised broadly: unneeded parts, inventions or activities; product defects; and time.
2. Amplify learning and discover solutions through short, repeated cycles of experimentation, and analysing results. This applies to both development and production, where development should be treated as an exercise in discovery and production as an exercise in reducing variation. Lessons learned must be captured, so mistakes are not repeated.
3. Development practice should provide for late decisions to be made in environments of uncertainty. Decide as late as possible and keep options open until the uncertainty is reduced such that it becomes possible to make more informed decisions. Choosing a particular technical solution early in development leads to late changes that are costly and end up causing delays.
4. Complementary but also somewhat contrary to point (3); deliver as fast as possible. Fast delivery means no scope for delays. In development, the discovery cycle is critical for learning: Design, implement, feedback (through customers or internally), improve. The faster these cycles are, the more opportunity there is for learning.
5. Empower the project team. No one understands the details better than the people who actually do the work. Involve developers in technical decisions to achieve quality.
6. Build integrity into the product to achieve a balance of function, usability, reliability, and economy that provides value to the market (or customer).

\textsuperscript{40} A useful analogy is to consider that development is designing a culinary recipe, and production is repeatedly producing the dish based on that recipe. In development quality is sought, which necessitates iteration to achieve (culinary) perfection. Production, on the other hand, considers quality as conformance to requirements where variable results and iteration generates waste (Poppendieck & Poppendieck, 2003).

\textsuperscript{41} Again, “lean” and agile are used somewhat synonymously in (Poppendieck & Poppendieck, 2003).

\textsuperscript{42} Also see (Sehested & Sonnenberg, 2010).
7. “See the whole”. Complex systems require deep expertise in many diverse areas, but experts tend to maximize the performance of the part of the product representing their own speciality rather than focusing on overall system performance. Ensure teams work with the overall engineering system in mind, as well as their own specialist areas.

Considering the lean principles above and referring to the co-evolution of agile and lean (2.5.32.5.3), it is evident that the two approaches operate on similar principles. For example, like agile, lean innovation promotes learning through discovery, emphasising the reporting of failure and learning from it, rather than minimising failure in the first place. Further, the way in which lean involves not making "decisions for or against any solutions before an adequate amount of information is available as a foundation" (Schuh, Lenders & Hieber, 2011). As such, when applied to development rather than quality management, lean can be interpreted as a directive that perfection must not get in the way of progress.

2.5.5.2. Applying lean innovation to fusion

As with the practical application of agile, there are methods to apply lean innovation in practice (Schuh, Lenders & Hieber, 2011). However, despite its origins in hardware, the focus on production rather than development means that – somewhat curiously – lean is not as readily applicable to fusion start-ups as agile. Despite this, there are several key principles from Deming’s 14 points that are useful: work on problems concurrently; work with collaborators as not all technology development can come from internal R&D (which also relates to open innovation, see 2.5.6); and big decisions should be made judiciously for the sake of expediency, because all decisions are – to some extent – made with incomplete information, and thus risk. However, other principles from lean production, such as the focus on “getting quality right the first time” and “only using reliable and tested technology” are not applicable. For the development of fusion, there should instead be more focus on learning from mistakes (which are more or less inevitable). In distilling the principles, however, it is possible to identify important criteria for the way fusion start-ups “do” innovation:

- Reduce the amount of waste. For instance, reviewing all potential future technology solutions to a particular challenge will permit selection of the optimal solution with minimal wasted time (also refer to the “Muda, Muri and Mura” concept in (Smith, 2014)).

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43 The Pareto principle that 20% of a products features will most likely deliver 80% of the benefits sought also relates to the MVP from agile innovation (see 2.5.4.2). The Pareto principle is considered in the context of lean innovation in (Agan, 2014).
- Learn through continuous iteration, building a product to test from which to learn (Deming’s *plan-do-check-act*).
- Accept late changes in requirements; uncertainty is inherent.
- Simultaneously, however, whilst late changes are accepted, changes should be avoided and new ideas implemented in the next iteration to avoid disruption (if the cycle time is fast enough).
- Assemble a team of creative experts at the base of the organisation as it scales up.

Finally, and importantly, the lean principle to “see the whole” can be interpreted to refer to the need to take a systems-view (see 2.2.3 and 2.5.5), i.e. that all processes, drivers and actors that impact technology development are considered. However, in the context of this thesis, it is interpreted to also refer to the need to *see the whole innovation process*, i.e. that inventions must have a commercial application. This is a particularly important consideration for fusion start-ups who – despite the commercial focus – are acutely focused on successful technology development, and inherently less on the commercial requirements.

2.5.6. Open innovation

2.5.6.1. Origins and principles of open innovation

Finally, distinctly different from agile and lean innovation is *open innovation*. Open innovation is based on the notion that a technology external to an organisation could be brought inside it to add value (or vice versa, i.e. where a technology developed inside an organisation could have value outside of that organisation) (Chesbrough, 2003; Fitzgerald, Wankerl & Schramm, 2011). It is the combination of “*internal and external ideas as well as internal and external paths to market to advance the development of new technologies*” (Chesbrough, 2003). Although open innovation was formally developed in the early 2000s, the fundamental need was recognised as early as the 1950s (“*Intra organisational innovation*” (Penrose, 1959)). Open innovation contends that the tendency for organisations to become overly focused on their internal technology solutions is something to be avoided and that organisations that exploit both internal and external R&D are more likely to succeed in commercialisation (Brem & Voigt, 2009; Chesbrough & Crowther, 2006). In response, many modern R&D-intensive companies have adopted an approach to R&D that encompasses open innovation, such as Proctor and Gamble (see (Lichtenthaler, 2011; Huston & Sakkab, 2006; Chesbrough & Crowther, 2006)). Lockheed Martin (again) provides a useful example here, whose Skunkworks division adopts an open approach to innovation (Chesbrough & Crowther, 2006). The differences between open and closed innovation are outlined in Table 2-2 and illustrated in Figure 2-8.
Closed Innovation | Open Innovation
---|---
Our organisation has all the internal expertise to carry out the work required. | Not all the expertise is internal. We must seek and leverage the knowledge and expertise of people outside of our organisation.
To get value from R&D, we must discover it, develop it, and protect it. | External R&D can create value, but internal R&D is needed to obtain some of that value.
If we develop the technology first, we will get to the market first. | We don’t have to carry out the research or develop the technology to profit from it.
If we are the first to market, we will be the most successful. | Building a stable business model and market strategy is better than focusing on getting there first.
If we develop the best and largest number of ideas in the industry, we are guaranteed to be the most successful. | If we can combine the best internal and external ideas, we will be more likely to be successful.
We must control intellectual property (IP) so that competitors cannot profit from our ideas | We should leverage our IP. We can profit from others using our IP, and we should buy others’ IP if it advances our organisation.

Table 2-2  Principles of closed and open innovation from the perspective of a company, compiled from (Chesbrough, 2003; Open Innovation EU, n.d.).

![Figure 2-8](image)

Figure 2-8  Closed innovation versus open innovation, recreated by the author based on the diagram in (Chesbrough, 2003). Note that competitive advantage can come from both “inbound” and “outbound” open innovation.

44 Inbound open innovation is an approach to leverage the discoveries of others; outbound open innovation takes an expansive view of potential paths to market (Chesbrough & Crowther, 2006).
2.5.6.2. Applying open innovation to fusion

Fusion start-ups face many complex and unknown challenges, and a multitude of technology areas require development on the edge of scientific possibility. Fusion start-ups cannot hope to solve all challenges alone, due to lack of resource, time and expertise. Typically, they are focused on technologies central to proving the success of their reactor concept in the near-term. Adopting an open innovation approach allows fusion start-ups to import external R&D solutions, selectively bringing technology in-house to support its mission, or even developing it further to yield new IP\(^{45}\). Specifically, some of the technology for fusion start-ups is likely to originate from the public fusion programme. Fusion start-ups can benefit from the existing R&D capability, established manufacturing techniques, and materials supply chains etc. On the other hand, such technologies may be unsuitable due to lack of applicability to the specific fusion reactor concept; the speed of delivery (because all focus or resource is elsewhere, on public fusion programmes for which it is being developed); high cost; or not a commercially-focused design (e.g. it produces high-level radioactive waste). The alternative is to seek to develop a professional network of existing entities which might not be experienced in developing fusion technology but have existing engineering capability that can complement specialist in-house expertise. Open innovation thus has an intrinsic link to the *innovation organisation* model, which outlines the need to engage with a range of institutions (labs, companies, suppliers, universities) to be involved in the creation, development and market introduction of a technology (see 2.5.1). The focus of the *innovation organisation* model on external partnerships and networks to help solve internal development problems further justifies its use as a foundation for innovation in fusion start-ups.

2.5.7. Combining agile, lean and open innovation for fusion start-ups

Agile, lean and open innovation have been reviewed, but the principles must be taken collectively and adapted to fusion start-ups. Once again, it is useful to consider the space sector to aid analysis. It has previously been informative to consider the SpaceX innovation approach, which is explored latterly. However, firstly, analysis of the well-documented *Pathfinder* mission; an unmanned mission to Mars conducted by NASA which landed successfully on Mars in 1997, and its – at the time, unintended – adherence to the principles of agile, lean, and open innovation is of value here.

\(^{45}\) Open innovation does not necessarily always have to be “fully” open, i.e. certain parts of programmes can be closed to protect IPR, is explored later in Chapter 4 and 5.
Pathfinder is deemed one of NASA’s great scientific successes, but also a success of project management (Muirhead, 1997). The project was predicated on the idea of conducting a challenging technology mission on a rapid schedule and low budget. The project was given license to take risks that were not typically accepted for planetary spacecraft such as using non-specific electronic parts (to reduce cost), limited use of documentation, and focus on hiring motivated people. Engineers were tasked with faster deployment, but with greater technological capability and at lower cost than previous NASA projects, see (Muirhead, 1997; McCurdy, 2001). The basis for the project was to accept high risk and an increased chance of failure, but simultaneously to design technology (or utilise) existing technology that was at the cutting edge and of low “commercial” risk (where, in this context, “commercial” related to “project cost”) (McCurdy, 2001). The Pathfinder project approach adhered to the following principles (adapted from (Muirhead, 1997)):

- Understand risks early and develop a strategy to solve or avoid them.
- Focus on simple solutions where possible.
- Use already qualified parts or existing technologies from outside of the space industry (including materials and processes), and adopt an error margin in using them.
- Involve creative scientists and give them technical freedom, guided by an experienced innovation manager.
- Create cost caps and deadlines, which must not be exceeded if the project is to be declared a success.

Today, companies such as SpaceX are emulating the Pathfinder approach, rapidly building and testing low-cost prototypes. The approach dictates that such prototypes must be relatively small and low-cost, to facilitate relatively short development cycle times. Such an approach facilitates forward progress even when the future is full of unknowns (Rigby, Sutherland & Noble, 2018). It also aligns well with the fundamental principle of agile, and – as interpreted in the analysis in 2.5.5.2 – lean innovation, i.e. to iterate fast, fail fast and learn fast. Similarly, the approach is also aligned with open innovation in its use of existing technologies from outside of the space sector. More recently, it is reported that SpaceX is “monitoring” new technologies and “waiting” for partners to emerge to solve its next steps (Rigby, Sutherland & Noble, 2018). Space sector start-ups like SpaceX and Pathfinder, therefore, have both applied agile innovation to hardware development. The innovation approach of such projects and missions the space sector – a similarly hardware-focused,

Refer to the PhD researcher’s reflections in 8.6.1.
with long timescales, many unknowns and high costs – can be, and to an extent already is, emulated by fusion start-ups\textsuperscript{47}.

By way of contrast, following this analysis, it is instructive to consider that the same approach to innovation is not apparent in public fusion programmes. Principally, it is the short development cycles and relatively simple (and small) prototypes where the major differences can be found. The length of the development times of large government projects such as ITER and DEMO (typically, decades – based on historical progress and current projects) limits the integration of the latest technologies or engineering advancements. Such long cycles thus limit the ability to test, fail and learn and – by virtue – late changes in the design result in cost overruns and delays. Such problems perpetuate, and further costs and delays are accepted on the grounds of reducing technological risk, which subsequently results in technology, to become outdated, i.e. the project becomes locked-in on a particular technology until the end of the cycle. The more complex a technology becomes, the more susceptible to such effects it becomes (Durney & Donnelly, 2015). For complex projects with a programme length of several years or more, this can result in slow and only incremental innovation at best, or a failed mission that is many times over budget and over schedule at worst. Arguably, aspects of both have manifested in the public fusion programme, particularly in the ITER project.

Table 2-3 provides a comparison of the approach of fusion start-ups and the public fusion programme from the perspective of agile and lean innovation\textsuperscript{48}. The table summarises the findings from the analysis in this section and complements the characterisation of fusion innovation in 2.3 and 0. It is important to note that while the table provides a description of the fusion start-up approach, it can also be perceived as a prescription for fusion start-ups seeking increased agility and leanness in their innovation approach.

\textsuperscript{47} The researcher specifically thanks Dr David Kingham and Dr Alan Costley at Tokamak Energy for ideas relating to the SpaceX-fusion start-up analogy.

\textsuperscript{48} Open innovation is considered to affect all stages of the innovation as an overarching philosophy. Further, aspects of the public fusion programme are likely to be “open”. As such, it is not included in the comparison.
<table>
<thead>
<tr>
<th>Agile innovation approach</th>
<th>Lean innovation approach</th>
<th>Government-led public fusion programme approach</th>
<th>Fusion start-up approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td><strong>Development</strong></td>
<td><strong>Changing requirements</strong></td>
<td><strong>People</strong></td>
</tr>
<tr>
<td>Keep it simple, minimise the amount of work done by avoiding unnecessary activities. It is easier to add features to a simple product or process than it is to remove features from a complex product or process.</td>
<td>Eliminate “waste”, where waste is characterised as anything that does not add value (including time spent on unnecessary activities).</td>
<td>Engineering design activity begins after a thorough technical understanding has been developed through comprehensive R&amp;D. Long timescales, high cost and complex design (e.g. ITER) are acceptable as long as risk is low and knowledge gained is high.</td>
<td>Limited resource and time forces progress without full technical know-how or understanding. Focus on simple design to ensure rapid development. Risk is acceptable and necessary to progress and to learn.</td>
</tr>
<tr>
<td><strong>Development</strong></td>
<td><strong>Changing requirements</strong></td>
<td><strong>Product</strong></td>
<td><strong>People</strong></td>
</tr>
<tr>
<td>Develop a working product and iterate (from which to learn). Reflect on how to improve the product; adjust and repeat. Mistakes provide valuable learning.</td>
<td>The best designs come from continuous iteration not from early, rigid plans. Embrace changing requirements, even late in development.</td>
<td>Satisfy the customer (or end-user) by quickly delivering a product that is imperfect (MVP), but which will benefit from continuous development and improvement over time based on customer feedback.</td>
<td>Build projects around people. Innovation occurs from human interaction and self-organised teams guided by a clear vision.</td>
</tr>
<tr>
<td><strong>Changing requirements</strong></td>
<td></td>
<td><strong>Development</strong></td>
<td>Build empowered development teams with authority to make decisions, under guidance rather than control from leaders. No one understands a product or technology more than the people who work on it.</td>
</tr>
<tr>
<td>The best designs come from continuous iteration not from early, rigid plans. Embrace changing requirements, even late in development.</td>
<td>Avoid locking in on decisions until unknowns are known but make late decisions in conditions of uncertainty; build a culture that can embrace change.</td>
<td>Focus on delivery to the customer as fast as possible – high speed results in rapid feedback and forces decisions. Reduce variation in standard production and processes.</td>
<td>Typically involves several large organisations with many scientists and engineers, in some cases sited across the world. Coordination and organisational aspects are necessarily regimented, which makes management and team cohesion challenging.</td>
</tr>
<tr>
<td><strong>Product</strong></td>
<td><strong>People</strong></td>
<td><strong>Government-led public fusion programme approach</strong></td>
<td><strong>Fusion start-up approach</strong></td>
</tr>
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</tr>
</tbody>
</table>

Table 2-3 The main characteristics of agile and lean innovation compared with the innovation approach of public fusion programmes and fusion start-ups.
2.5.7.1. A Minimum Viable Product for fusion start-ups

One aspect of both agile and lean innovation that is fundamental for fusion start-ups is the approach towards technology development, i.e. for agile the “build-measure-learn” towards an MVP, and for lean the “plan-do-check-act” for continuous product improvement (Ries, 2011; Agan, 2014; Poppendieck & Poppendieck, 2003). As agile innovation is more attuned to the development phase, it is more apposite to employ the agile innovation MVP. It is suggested that an MVP for a fusion start-up is a device that is capable of demonstrating the commercial viability of fusion. Such a device must thus demonstrate solutions to technical challenges but must also subsequently scale to a commercial device (see (Ries, 2011)). Significantly, therefore, a fusion MVP must reach this point as quickly and at as low a cost as possible, whilst simultaneously preparing for the next steps beyond it (i.e. bridging the gap between the MVP and the commercial market). Determining what is needed for a fusion MVP is, therefore, a difficult but crucial task. To design an optimal fusion MVP, it is necessary to understand the pathway to commercialisation and to be aware of the future challenges on that pathway.

It is likely that several test devices will be needed before an MVP can be built. Such devices are required to improve understanding of the physics, build engineering capability, and to raise investment. It is, therefore, appropriate to consider the steps towards an MVP as minimum viable demonstrations (MVDs). MVDs can then be designed as targets for technology performance, and also to understand the non-technical problems such as material supply chains, the regulatory environment etc. that must be tackled and solutions developed in parallel. MVDs can thus act as milestones towards an MVP. However, deciding how complex an MVD is not straightforward. It should focus on developing and demonstrating key enabling technologies for the MVP. At the same time, however, features that facilitate the next steps must also be incorporated without introducing waste (see 2.5.5), delays, or added cost. Importantly, the approach to development via a series of MVDs should provide some structure to support a cycle on which to build, test and learn. A critical MVD on the path to an MVP is the demonstration of first net power gain, i.e. a device capable of surpassing the fusion version of the “Wright Brothers” moment. It is expected that the first fusion start-up (or start-ups) to realise this MVD will see a surge of interest and investment akin to that seen during the pioneer era of aviation sparked by the first demonstration of controlled flight by the Wright brothers (Penrose, 1979). As such, it can be here considered as the “breakthrough MVD”. MVDs can be identified to show the advancement of key technical issues for the realisation of the MVP, thus collectively, they chart the overall progression towards commercialisation, as shown in the diagram in Figure 2-9.
Crucially, a breakthrough MVD must be scalable to the MVP. In other words, all features must support rather than hinder the next steps to commercialisation; “shortcuts taken today may wind up causing a slowdown tomorrow” (Ries, 2011). Ideally, a breakthrough MVD would simultaneously build scientific confidence and offer a clear route ahead to a commercial product; of significance to scientists and investors, respectively. It is useful to reconsider the success of the Wright Brothers, whose 1903 Flyer did not translate into a functional aircraft immediately thereafter, and it most certainly it did not look anything like even the earliest commercial aircraft (Kline & Rosenberg, 1986). Instead, the 1903 Flyer demonstrated viability by overcoming several critical technical hurdles that facilitated the next steps; most crucially that the scientific feasibility was no longer in doubt. Perhaps without realising it, the Wright Brothers developed aspects of their aircraft that were on the critical path that facilitated the subsequent boom in aviation entrepreneurship.

It is interesting to note that while the Wright Brothers were the first to achieve technology demonstration, they did not achieve commercial success, showing that it is not necessarily technological success that ends up winning in the market. As such, as detailed in 2.5.4.2., commercial drivers must be considered in the development of the breakthrough MVD and the MVP. Most obviously, the selected market conditions for the commercial product must be understood, and the cost should be aligned with what is viable for the market. However, technologies – which are often seen purely as technical challenges – have inherent and important commercial drivers. For the development of fusion, tritium supply (explored in chapter 6); tritium breeding (explored in chapter 7); the development of advanced materials; and even plasma stability (i.e. whether a plasma can be sustained for a long duration) all have commercial challenges, as well as technical ones, that must be overcome.

49 Incidentally, Ries notes that convincing scientists of the MVP concept can be difficult as it is viewed as “low quality” and is thus undesirable as a technical endeavour (see (Ries, 2011)).

50 Refer to 2.3 and (Kline & Rosenberg, 1986) for the case of Concorde and the Comet I jet.
2.5.7.2. **Summary of the innovation approach for fusion start-ups**

The core elements of the innovation approach of fusion start-ups, particularly in the context of agile and lean innovation, have been analysed. The analysis has yielded both a description of and a prescription for the fusion start-up approach to innovation. Accordingly, it can be determined that fusion start-ups follow/should follow an approach that:

- Accounts for all aspects of the innovation process by following, e.g. the innovation organisation model, and by considering commercial aspects (not just technological).
- Focuses on the development of low-cost, small and simple devices (at least relative to devices developed on the public programme).
- Encompasses agile and lean innovation principles, in particular, following an iterative “build-measure-learn” or “plan-do-check-act” cycle.
- Encompasses open innovation by using existing technology or partners, including from outside of the fusion sector.
- Works towards the realisation of an MVP via several MVDs, including a critical **breakthrough MVD** to demonstrate net power gain.

### 2.6. Plotting a route to commercial fusion

As shown in 2.5.7.1, developing MVDs and an MVP for fusion requires an understanding of the pathway to commercialisation, and thus – by virtue – an understanding of the future stages of the innovation process. It is contended that a tool to manage or guide innovation is needed to support fusion start-ups in developing towards commercialisation. However, it is first useful to explore the development of technology in the context of models that help to understand the dynamics of the innovation process from initial concept to market. Such models have explored existing industrial contexts which provides insights for the fusion context.

#### 2.6.1. Models of industrial emergence

The stages of the innovation process can be mapped to effectively plot the emergence of technology from the early stage through to market. Such models are known as models of industrial emergence; theoretical models that map the stages of innovation to depict how industries evolve, grow, mature and thrive or collapse (Phaal et al., 2011; Gallagher, Holdren & Sagar, 2006; Hekkert et al., 2007). In the real-world, such emergence typically follows an “S-curve” trend, see Figure 2-10 and (Routley, Phaal & Probert, 2013).
Several models of industrial emergence have been developed to support analysis of the dynamics of innovation. Figure 2-11 provides the researcher's interpretation of the innovation process based on several key models.
The typical stages of industrial emergence, shown as steps I-V, collated from (Klepper, 1997; Suarez, 2004; Gallagher, Holdren & Sagar, 2006; Phaal et al., 2011).

2.6.2. The S-T-A-M model of industrial emergence

All models of industrial emergence are based on trends seen in previous examples of industrial emergence. As such, they provide some degree of confidence in understanding and plotting other systems – in particular, engineering systems – and their dynamics (Phaal et al., 2011). The S-T-A-M (Science-Technology-Application-Market) model of industrial emergence is suitable for application to the fusion context as it is focused on mapping the evolution of technology-intensive industries and because it is an advancement on and incorporation of several earlier similar models.
The S-T-A-M model delineates the core phases of the innovation as progressing from science (S), to technology (T), to application (A) to market (M), hence “S-T-A-M”\(^5\). The S-T-A-M model is applicable to a variety of contexts, but – naturally – it must still be adapted to suit the scope, stage, and timescale of the problem to which it is being applied. Figure 2-12 shows the S-T-A-M model showing a typical path from scientific discovery to commercial market for a technology-intensive industry.

Each stage of the model, and the transitions between stages (denoted by the hyphens in the name), require interpretation. The science (“S”) phase of the model focuses on R&D to demonstrate the science. The transition to technology (“T”) requires first a successful demonstration of the science to show it is technically viable. Subsequently, the functionality of the technology must be demonstrated, i.e. it must show that it has a commercially useful application (“A”). Finally, the application must be developed to be commercially viable, to go to market (“M”). The transitions between each stage, which are referred to as “stage-gates” or “milestones” in other similar models, see (Cooper, 2008), can be considered as key decision-making points that enable practical goals to be established and as an indication of the start of the next stage of innovation. As such, while the stages of the S-T-A-M model are broadly analogous to the innovation process, the transitions – or more

\(^5\) The S-T-A-M model can be separated into two levels: “S-T-A-M” and “s-t-a-m” (upper and lower case). Upper and lower case shows the emergence of an entire industry versus the emergence of a single organisation, respectively (Phaal et al., 2011). In this thesis, for simplicity, only one tier of the model is considered.
specifically the “demonstrators” that are used to demonstrate progress through the transition – are interpreted here to be analogous to MVDs and the MVP, as shown in Figure 2-9.

Importantly, while the model appears as a linear progression, it must be viewed with the understanding that – like all systems innovation models – that the process is dynamic, see (Routley, Phaal & Probert, 2013). Mapping the dynamics of the innovation process in graphical format is counterintuitive, as discussed in (Phaal et al., 2011).

2.6.3. Fusion in the context of the S-T-A-M model

It is assumed that fusion will follow a similar trajectory to that shown in the generic S-T-A-M model, given that it is derived from innovation in real-world case studies. If the fusion development in the public programme were to be plotted, then the S-T transition would be the demonstration of net power gain; the point at which the breakthrough MVD is realised. The breakthrough MVD is, therefore, ITER. Tokamak reactors such as JET and JT-60 might then be considered as “early scientific demonstrators” (MVDs) leading up to ITER. The subsequent step, to demonstrate useful power production from a prototypical fusion reactor, is a principal goal for a next-step DEMO reactor. DEMO, therefore, represents the device to cross the T-A transition, and thus represents the MVP. After DEMO, an as-yet-unspecified “first of a kind” (FOAK) fusion reactor will demonstrate commercial viability and take the fusion industry across the A-M transition. Thereafter, the FOAK can be developed for the market. This trajectory for the public programme is shown in Figure 2-13.

![Figure 2-13 The public fusion programme in the context of the S-T-A-M model.](image)

All fusion programmes are primarily focused on the demonstration of power gain. Accordingly, fusion development is typically plotted on a diagram showing scientific progression towards net power gain, i.e. the Lawson diagram (as shown in Figure 1-1, also
see (Clery, 2019)). Although useful for gauging scientific progress, the Lawson diagram only highlights the advancement of fusion in the science (“S”) stage of development, i.e. before the S-T transition. As such, the S-T-A-M model provides a unique perspective as regards the commercialisation of fusion. ITER is expected to demonstrate net power gain around 2035, and DEMO will begin its operations around 2050 or later, and a commercial FOAK has not yet been planned (designs are in the pre-conceptual stage). Based on this trajectory, therefore, market-deployable fusion energy is expected to arrive sometime in the second half of the 21st century. Even then, if the design of a FOAK for 2070 is technologically remarkable, how it performs in the market is unknown – as market needs in 20 years, let alone 50 years, will be dramatically different.

Fusion start-ups are on a similar trajectory and are similarly focused on demonstrating net power gain, i.e. fusion’s “Wright Brother’s” moment. Naturally, fusion start-ups are at a different level of technical maturity than the public programme (albeit that private start-ups pursuing tokamaks are – by virtue – most advanced). Fusion start-ups are pursuing an approach that focuses on shorter innovation cycles between the same stages of the industrial emergence expected for the public fusion programme, as shown in Figure 2-13. The public fusion programme is operating on a cycle in which there are around 20 years between devices. In contrast to the public programme, therefore, fusion start-ups must target timescales measured in the order of years, rather than decades.

By adopting an iterative approach; by viewing the innovation process as dynamic (i.e. that all phases of the innovation process affect each other); and by adopting a fail-fast learn-fast philosophy facilitated by a higher acceptance of risk, fusion start-ups have an opportunity to accelerate development.

2.7. The need for innovation management in fusion start-ups

This chapter has detailed the process, models and principles that underpin innovation in fusion start-ups. However, that innovation process is not often organic or autonomous – it is grappling with a future full of challenges and opportunities, which requires tools and techniques to navigate it (Ries, 2011; Bonvillian & Weiss, 2015; Hekkert et al., 2007). As indicated, there is a need to consider all stages of the innovation process in developing a strategy; as trying to conduct innovation without a strategy is “as likely to lead to self-destruction of creative enterprises as it is for creative destruction” (Teece, 2010). Pisano defines a strategy as coherent, mutually reinforcing policies, behaviours and objectives aimed at achieving a specific goal that promotes alignment within an organization (Pisano, 2015). Together with the definition of innovation from 2.2.1, an innovation strategy is thus a set of processes and structures to identify future challenges and opportunities, explore potential solutions associated with how a technology will be turned into a product that will
achieve commercial success. To develop an innovation strategy requires first an understanding, then management, of the innovation process. Management methods, tools and techniques support the development of an innovation strategy.

Fusion start-ups are founded upon creativity and invention, but they are not always suited to planning, or to the execution of plans. They are also heavily focused on the early stages of the innovation process, i.e. R&D, which is typical of early-stage technology start-ups, see (Freeman & Engel, 2007). Long-term goals are often overlooked in favour of the next deliverable. As a result, the latter stages of the innovation process, e.g. the identification of markets for the technology being developed, and the corresponding features that would be required for a fusion reactor to address that market, cannot be considered in-depth due to such a long time horizon (Hannola, Friman & Niemimuukko, 2013; Freeman & Engel, 2007; Albright & Kappel, 2003). The diagram in Figure 2.14 is instructive in this regard, as it shows the scope of technology, R&D and innovation management. Technology management and R&D management have long been at the centre of focus in fusion.

![Diagram showing the scope of technology, R&D and innovation management](image)

**Figure 2.14** Differences between R&D, technology and innovation management in the context of the overall innovation process, adapted with permission from (Brem & Voigt, 2009).

This thesis contends that fusion start-ups would benefit from innovation management, and – moreover – methods to support innovation management, to realise commercial fusion. Innovation management may not seem as “heroic” as the invention of a novel technology to some fusion scientists or engineers, but without a view of how to take inventions to market (i.e. focusing only on R&D management), pioneering organisations may be deprived of ever being rewarded for their technological success (Teece, 2010a).

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52 It is necessary to mention business models as a concept. A business model shows how a company will make profit. Fusion start-ups are developing early-stage technology towards a product, which will ultimately produce profit. The management of innovation relates to the process to develop technology from R&D to market. Innovation management and business models are thus inherently intertwined. See (Teece, 2010a).
There are many processes and tools that are available to support organisations in managing innovation. Of particular utility are *Futures* methods; methods that support future planning and forecasting which have been developed via a combination of research and practice. Such methods necessarily take a high-level, overview approach aiming to determine the most effective near- and mid-term activities to deliver long-term goals. The next chapter will consider potential futures research methods, with a view to selecting a suitable method to help manage innovation and support development in fusion start-ups.

2.8. **Chapter summary**

To the best of the researcher’s knowledge, the analysis in this chapter represents the first in-depth application, characterisation and contextualisation of the principles of innovation models, as well as agile, lean and open innovation to the fusion and – specifically – the fusion start-up context.

The learning outcomes, which are used to explicitly answer Research Question 1 in Chapter 8, are here summarised:

The innovation approach of the public fusion programme (principally via ITER) and fusion start-ups has been explored through extensive analysis of the innovation literature. The public fusion programme is found to predominantly operate on a *linear model of innovation* (2.3). Emerging fusion start-ups are inherently focused on commercialising novel fusion technologies, and it is found that they are operating on a different model of innovation (2.4). Crucially, the received wisdom that fusion is only possible by means of government-led programmes appears inconsistent when analysed in the broader context of industrial innovation. Accordingly, it is contended that a paradigm shift towards fusion start-ups is underway. The innovation approach of fusion start-ups is thus characterised, particularly in the context of agile and lean innovation; both a description and a prescription for the fusion start-up approach has been detailed (2.5). Finally, with reference to models of industrial emergence (2.6), it is suggested that fusion start-ups would benefit from innovation management (2.7).

The identification of the need for innovation management provides foundations for Research Question 2, which is addressed in Chapter 3, 4 and 5 of this thesis.
Chapter 3. Technology Roadmapping

This chapter will explore potentially suitable methods for innovation management. A method is selected based on suitability for application to the fusion start-up approach outlined in Chapter 2. Therefore, this chapter provides the foundations upon which Research Questions 2A and 2B can be addressed in Chapters 4 and 5, respectively.
3.1. Futures research

The future is inherently unknowable, and thus not entirely predictable (European Industrial Research Management Association (EIRMA), 1997; Gordon, 1992). Over the course of the 20th century, a wide range of futures research methodologies emerged, from a variety of origins – sociology, social and political sciences, economics and systems (Gordon, 1992; Weingand, 1995; Boyd, Melis & Myers, 2004). One of the core principles of futures research is that exploration of what the long-term may look like can inform decisions that must be made in the near-term (Weingand, 1995; Boyd, Melis & Myers, 2004). Without probing deeply into the philosophy as to whether there are one or multiple possible futures as illustrated by Figure 3-1, Futures research should be understood as looking forward to determine the potential actions and sequences that are required to cause or affect the probability of a particular – typically, desirable – future event (or events) to occur. Futures methods thus provide a basis for making decisions that will lead to the preferable futures and avoid the undesirable futures.

![Figure 3-1: Interpretation of possible, probable and desired futures, reproduced with permission from (Lindgren & Bandhold, 2003).](image)

3.1.1. Futures methods

A variety of different methods have been developed in a multitude of different research fields, which have been widely adopted to support long-term planning in governments as well as in private organisations (Amer & Daim, 2010; Gordon, 1992; Porter et al., 2004;
Weingand, 1995; Boyd, Melis & Myers, 2004). Futures methods can be objective or subjective, qualitative or quantitative, and explorative or normative. Explorative methods can be used to explore futures that seem plausible, often based on historical trends or data, whilst normative methods provide forecasts of desirable futures (Gordon, 1992; Lindgren & Bandhold, 2003). The two approaches are shown in Figure 3-2, where “feed-forward” and “feedback” are synonymous with explorative and normative, respectively.

![Figure 3-2](image)

**Figure 3-2** Different mechanisms of Futures research (feed-forward and feedback), reproduced with permission from (Lindgren & Bandhold, 2003).

Futures research methods provide insights and understanding on how systems – societal, political, technological, or otherwise – might evolve in the future, providing a means to plan to avoid the worst scenarios and to steer towards the best. An important underpinning principle of all futures methods is that the future cannot be predicted, only planned for but that doing something is better than nothing\(^{53}\) (Weingand, 1995; Gordon, 1992; European Industrial Research Management Association (EIRMA), 1997). Commonly, such an approach employs the term “forecasting” – defined as the process to identify patterns of behaviour and how these patterns change or continue and thus how they affect a system or particular aspect of a system\(^ {54}\) – which often invoke thoughts that the future is knowable. The term must be clarified: if an undesirable future is forecast, then policies or actions can be put in place to mitigate the probability of that particular future coming to fruition. If effective, such policies or actions can render original projections to be wrong. This indicates

\(^{53}\) This notion can be tied – quite famously – to U.S. President Dwight D. Eisenhower who claimed in several speeches that “plans are worthless, but planning is everything”.

\(^{54}\) Different futures methods can be applied to systems problems in different contexts (refer to 2.2.3). Certain methods and tools can be applied to engineering systems, and others to political or social systems. However, many such methods are cross-cutting.
that the very act of forecasting, and subsequent actions to address the forecast, is self-
prophesising. However, only in cases of extremely limited time or scope can forecasting be
close to precise, and Futures methods should instead be seen as providing “foresight”
rather than “forecast” (see (Miles, 2010; Martin, 2010)). Gordon perhaps most aptly
describes that futures methods are not a “crystal ball”, but instead provide a reminder that
one does not have a crystal ball (Gordon, 1992). Consequently, methods for successful
foresight are often based around regular or continuous review.

3.1.2. Assessing Futures methods for the application to fusion start-ups

Futures methods that can increase understanding and identify the range of possible futures,
as well as the potential challenges and opportunities, are particularly important in
technology-related sectors (Martin & Irvine, 1989; Martin & Johnston, 1999). This section
explores futures methods that may be useful for application to fusion start-ups in developing
technology towards commercialisation. Specific futures methods are assessed specifically
against the following criteria from Martin and Irvine’s “5 Cs for successful foresight” (see
(Martin & Irvine, 1989)):

1. Concentration on long-term issues
2. Coordination of future-based thinking (i.e. management of views of the future)
3. Communication about the future
4. Consensus on what the desired future looks like
5. Commitment to carrying out the actions to achieve the desired future

The 5 Cs will later be used to inform specific objectives for the research, see 0.

3.1.2.1. Overview: System Dynamics

System Dynamics originated from the Massachusetts Institute of Technology Sloan School
of Management in the 1950s to help understand how management could improve the
efficiency of industrial processes (Sterman, 2000). Based on the notion that social systems
are much harder to understand and to control than physical ones, i.e. they are complex and
dynamic, the method subsequently evolved to become a method to assist in the
understanding of complex systems (Sterman, 2001). As such, principally through
modelling, System Dynamics focuses on the patterns of behaviour rather than the elements
of the system itself\(^{55}\). It provides an understanding of the effects of causality and feedback,
the accumulation and movement of stocks (e.g. resources, products, people) accounting
for the time delays across a system, which result in non-linearity and often counterintuitive

\(^{55}\) See 2.2.3.
behaviour\(^5^6\) (Sterman, 2001; Richardson, 2011; Sterman, 2000). System Dynamics can thus support the understanding of what might happen if a policy or action is introduced to a system as a whole, provided that it has been accurately modelled, which allows better decision-making (Sterman, 2001). Of critical importance in System Dynamics is feedback. Feedback is found in most real-world systems and imperative to understanding system behaviour. By quantifying how components of a system interact via causal loops and stock-flow feedbacks, models can be developed to show that instabilities in a system are usually due to internal forces or instabilities, and not always by external factors. As such, the technique has been applied widely to test or monitor the implementation of policies or actions in a variety of future-based contexts (see (Radzicki & Taylor, 2008; Hubbert, 1962; Naill, 1992; Sterman, 2000)). An example of a System Dynamics model is provided in Figure 3-3.

Figure 3-3   A System Dynamics model for Bass diffusion (market adoption), showing stocks, flows and causal relationships as interacting feedback loops, (Sterman, 2001).

3.1.2.2. **Overview: Scenario Planning**

Scenario Planning is a method for anticipating change and learning about the future by understanding the nature and potential impacts of the most uncertain and important driving forces (Lindgren & Bandhold, 2003). It is a hypothesis-based method that outlines possible future by constructing a range of possible situations, holistically combining creative and imaginative future-based thinking with strategic planning (Weingand, 1995; Gordon, 1992).

\(^{5^6}\) See “policy resistance” in (Sterman, 2000).
Hence, it has been used to visualise future social, political, cultural, economic and technology futures (Forestry Department Policy and Planning Division (United Nations), 1996; Davis, 2002). A visual representation of scenario planning methods is shown in Figure 3-4.

![Scenario Planning methods](image)

**Figure 3-4**  *Scenario Planning methods, recreated by the author based on the diagram in (Davis, 2002).*

The basic steps in Scenario Planning method are detailed as (adapted from (Davis, 2002; Camarinha-Matos, 2009)):

1. **Identify**: Determine a focal issue or critical decision
2. **Analyse**: Assess internal and external driving forces
3. **Imagine**: Build scenarios using a scenario method (Figure 3-4)
4. **Decide**: Identify potential options to achieve desired future scenario(s)
5. **Act**: Develop a plan and monitor factors affect the scenario

Simply, a scenario must tell a story with plausible cause and effect links that connects a future condition with the present, while illustrating key decisions, events and consequences throughout the narrative. Scenario planning is conducted with the understanding that no scenario represents the actual future, and that the reality is that it will likely be a mix of all scenarios that have been considered, and more (Gordon, 1992; Weingand, 1995). Despite this, scenarios must be internally consistent (not self-conflicting), free of bias and grounded in reality, i.e. even if the probability of the scenario occurring is low; the scenario must be plausible (Gordon, 1992). Accordingly, scenarios are only valid if a series of events,
conditions or actions required to achieve the preferred future can be described (Forestry Department Policy and Planning Division (United Nations), 1996).

3.1.2.3. Overview: Delphi

The Delphi method was originally developed by the RAND (Research ANd Development) corporation as a structured process to collect expert knowledge on a particular issue by controlled feedback, see (Dalkey, 1967). The process is iterative, eliciting expert ideas individually and confidentially around a specific issue in a controlled manner until a general consensus (or significant divergence) is reached. The flexibility of the Delphi method means it has been and can be adapted to many contexts. The method collects and combines expert viewpoints whilst avoiding the pitfalls of “conference room confrontations” and opinion bias (such as “groupthink”), by controlled (or “blind”) sequential feedback (Camarinha-Matos, 2009; Gordon, 1992), like that shown in Figure 3-5.

![Figure 3-5](image)

*Figure 3-5  Example of an adapted Delphi method, reproduced with permission from (Heuer & Pherson, 2010).*

The broadest hypothesis is that experts, particularly when they agree, are more likely than non-experts to be correct about future developments in their field (Gordon, 1992; Loye, 1998). As such, results of the Delphi process can be implemented upon the notion that they provide the best possible view of the way forward (Weingand, 1995; Gordon, 1992; Helmer-Hirschberg, 1983; Dalkey, 1967).
3.1.3. Assessing the suitability of futures methods to support fusion start-ups

The suitability of each of the methods that have been detailed is assessed against the 5 Cs in Table 3-1 below. The suitability of each method is subsequently discussed\(^{57}\).

<table>
<thead>
<tr>
<th>Criteria for successful foresight</th>
<th>System Dynamics</th>
<th>Scenario Planning</th>
<th>Delphi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Coordination</td>
<td>✓</td>
<td>~</td>
<td>X</td>
</tr>
<tr>
<td>Communication</td>
<td>~</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Consensus</td>
<td>X</td>
<td>~</td>
<td>✓</td>
</tr>
<tr>
<td>Commitment</td>
<td>✓</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

*Table 3-1 The methods of System Dynamics, Scenario Planning and Delphi against the criteria for successful foresight. "~" indicates conditional, i.e. the method can be adapted, but it is not directly suitable.*

The table shows each method has different functionality and could be applied to support fusion start-ups, but overall suitability must also be evaluated qualitatively.

3.1.3.1. Assessing suitability: System Dynamics

A System Dynamics model for fusion start-ups would be capable of communicating potential futures and could provide the analysis (coordination) of long-term issues. This would allow for scenarios or certain actions to be modelled to understand the impact of certain decisions. However, a System Dynamics model cannot necessarily show the steps required to get to a future desired point. Even if a fusion start-up system could be modelled in System Dynamics, whilst of academic interest, it may have little real-world value to fusion start-ups needing to guide them through the innovation process. In the context of this research, the method of System Dynamics is too complex and quantitative. It focuses more acutely on understanding "why", rather than "how", which has less utility in planning for and managing innovation in fusion. In reviewing the limitations of System Dynamics, however, it can be seen that an explorative and qualitative method would be better suited for application to fusion start-ups.

\(^{57}\) SWOT analysis and PESTEL (also known as PEST, STEEP or STEEPLE) analysis were also explored but are not included as they are considered tools rather than methods. The utility of such tools is detailed in Chapters 4 and 5.
3.1.3.2. Assessing suitability: Scenario Planning

Scenario Planning is well suited to the task of dealing with paradigmatic, non-linear change (Lindgren & Bandhold, 2003; Martin & Johnston, 1999). As such, it is well aligned with the S-T-A-M model for industrial emergence (2.6.2). However, unlike System Dynamics, Scenario Planning does not provide a means to understand the system being modelled. Despite its utility to find consensus on what the desired future may look like; exploratively mapping and communicating the vision for that future, it is limited in understanding the specific actions required to achieve that future. The capability of Scenario Planning to support the management of the innovation process is thus limited. Nevertheless, as indicated, Scenario Planning might represent a viable method to understand what a desirable future (or futures) look like, as well as a means to understand the broad steps to get there. In particular, in many ways, Scenario Planning could be used in conjunction with the S-T-A-M model and the MVD/MVP trajectory outlined in 2.6.3.

3.1.3.3. Assessing suitability: Delphi

The Delphi method is well suited to long-range problems in which there are various unknowns. Also, with its inherent focused on communication and consensus amongst experts (and leaders), Delphi appears well suited to support the development of long-term plans and to help navigate the innovation process. Despite its important function to communicate about the future, and to identify actions, it is limited in that it cannot be used to understand the relationships between the components of the system. Instead, it is more aligned with, or perhaps even complementary to, Scenario Planning. As a standalone method, however, its utility for innovation management is also limited.

3.1.4. Assessing Technology Roadmapping as a Futures method

The futures methods explored thus far; System Dynamics, Scenario Planning and Delphi have limitations such that they are impractical, incomplete or for the application to fusion start-ups to manage innovation, and in particular on complex engineering systems. To some extent, however, they are not competing methods but in fact, complementary – where aspects of each method are useful depending on the application. Technology Roadmapping is a Futures method that appears to combine and align several key aspects of System Dynamics, Scenario Planning and Delphi. Technology Roadmapping is explored as a potentially suitable method for application to fusion start-ups.
3.1.4.1. Overview: Technology Roadmapping

Although its true origins may have been earlier, Motorola is widely credited with developing the technique of Technology Roadmapping in the late 1970s to support strategic planning (Phaal, Farrukh & Probert, 2010; Willyard & McClees, 1987; Richey & Grinnell, 2004). The principal function of Technology Roadmapping is to identify the desired (or expected) future position, define the current position, and to plot a pathway between the two; mapping a route from “where we are now” to “where we want to be”, to determine near-term actions that are required to deliver long-term goals (Phaal, Farrukh & Probert, 2010; Amer & Daim, 2010). Winebrake thus describes roadmapping as “a future based strategic planning device that outlines the goals, barriers, strategies necessary for achieving a given vision of technological advancement” (Winebrake, 2004). Many variations of the Technology Roadmapping method exist which vary substantially depending upon the application. The roadmapping process – naturally yields – a Technology Roadmap. A Technology Roadmap is a multi-layered time-based chart on which the evolution of a particular industry, market, product or technology is plotted (Phaal, Farrukh & Probert, 2010). The generic structure of a Technology Roadmap, which clearly shows the adaptable layered structure, is shown in Figure 3-6.

If designed appropriately, Technology Roadmaps can be used to consider both the technical and commercial aspects of development that are required for effective innovation (see (Phaal, 2004; Kostoff & Schaller, 2001; Phaal, Farrukh & Probert, 2010)). As such, an effective Technology Roadmap will show the technology or product development steps, the

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58 See (Beeton, 2007).
identified opportunities, challenges or risks, and the resources on the route to market deployment and diffusion (Garcia & Bray, 1997; Phaal, Farrukh & Probert, 2010).

3.1.4.2. **Assessing suitability: Technology Roadmapping**

The suitability of Technology Roadmapping as a method is considered, with reference to the 5 Cs, in Table 3-2.

<table>
<thead>
<tr>
<th>Criteria for successful foresight</th>
<th>Technology Roadmapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>Takes a holistic view of the engineering system, whilst considering all stages of the innovation process to inform the development of action plans</td>
</tr>
<tr>
<td>Coordination</td>
<td>Creates a Technology Roadmap that shows the key challenges and opportunities to be identified, mapped and explored</td>
</tr>
<tr>
<td>Communication</td>
<td>Creates Technology Roadmaps that portray a concise yet integrated view of the desired (or expected) future, providing a visual tool for communication</td>
</tr>
<tr>
<td>Consensus</td>
<td>Gathers the views of multiple stakeholders, typically via workshops, in which ideas of what future should look like can be discussed and aligned</td>
</tr>
<tr>
<td>Commitment</td>
<td>Provides a tool that enables the development of a strategy or action plan to angle towards the desired future.</td>
</tr>
</tbody>
</table>

*Table 3-2 Technology Roadmapping compared with the criteria for successful foresight.*

Technology Roadmapping is well suited to problems that require long-range planning and the consideration of complex systems. It is also uniquely aligned with the innovation process, particularly in the way in which technical and commercial drivers are considered simultaneously (see 3.3.2). Furthermore, the principles that underpin the structure of the innovation process in the S-T-A-M model of industrial emergence can also be readily applied to roadmapping, as shown in (Phaal et al., 2011). Finally, and importantly, Technology Roadmapping brings together key aspects of all of the aforementioned futures approaches, as it borrows heavily from other established technology futures methods (Kappel, 2001). Technology Roadmapping is inherently similar to Scenario Planning in developing a view of potential futures, and mapping actions to achieve the most desirable future (see (Hussain, Tapinos & Knight, 2017) in which Technology Roadmapping and Scenario Planning are combined). Similarly, the focus on collective development, particularly via workshops, is akin to the Delphi method (see (da Silveira Junior et al., 2018; Kanama, 2013)). Finally, whilst time is explicit in a Technology Roadmap and implicit in System Dynamics, the function of both methods to consider all elements in complex
systems makes them obliquely similar. In particular, refer to (Geum, Lee & Park, 2014) in which Technology Roadmapping and System Dynamics are combined, along with elements of Scenario Planning.

In summary, roadmapping is a suitable method to support the management of the innovation process in fusion start-ups, in particular, due to its high adaptability and because it can integrate various tools and techniques, see (Albright & Kappel, 2003; Garcia & Bray, 1997; Kostoff & Schaller, 2001; Phaal, Farrukh & Probert, 2001b). The next sections detail the method of Technology Roadmapping before detailing how the method could be developed specifically to support fusion start-ups.

3.2. Technology Roadmapping as a method

3.2.1. Overview

Technology Roadmapping, hereafter referred to simply as “roadmapping”, is well suited to technology development projects due to its adaptability, flexibility and inherent capability to consider both the technical and commercial aspects of development simultaneously, and the interactions between these elements (Amer & Daim, 2010; International Energy Agency, 2014; Albright & Kappel, 2003; Phaal, 2004; European Industrial Research Management Association (EIRMA), 1997). Roadmapping can also support a better understanding of the type of business model required by aligning identified market needs with product features, or by identifying potentially disruptive technologies to inform R&D needs (Courtney, Kirkland & Viguerie, 1997; Phaal, Farrukh & Probert, 2010; Albright & Kappel, 2003).

59 For clarity, the differences between roadmapping and business models should be understood. A business model describes how an organisation creates and delivers value to its customers, and how it converts that product or service into profit (Teece, 2010a). Roadmapping can accommodate aspects of the business model, for instance by showing value streams, or by connecting the value streams to inform required technology R&D (Dissel et al., 2009). Moreover, it can help to identify the best type of business model or to even support a transition to a new business model (Abe et al., 2009; Phaal, Farrukh & Probert, 2010).
Figure 3-7 Details of a roadmap, reproduced with permission from (Phaal, Farrukh & Probert, 2010).

Figure 3-7 provides a more detailed schematic of a Technology Roadmap (which, like the shortening of the word “roadmapping”, is hereafter referred to as a “roadmap”). The diagram shows how a roadmap captures information from various functions, e.g. product and science (see “roadmap architecture”) and places these in the context of time using the questions, “where do we want to go?”, “where are we now?” and “how do we get there?” Furthermore, it illustrates how the different drivers drive enquiry, the “why”, “what” and “how” (see “knowledge types”). In fact, roadmaps also address the “when”, “who”, and “where”, too. Colloquially these questions are known as the “6 W’s”, which can be traced back to a famous poem by Rudyard Kipling’s “six honest serving men”. The six questions can be used to guide scientific enquiry, as a well-structured study will provide answers to all (Sharp, 2002; Kappel, 2001; Phaal, 2004; Ellis & Levy, 2008; Kerr, Phaal & Probert, 2013). In a roadmap, typically, the time function implicitly addresses “when”, whilst the “why”, “what” and “how” aspects can be shown as layers, and the “who” and “where” can be embedded in the details of a roadmap itself.

3.2.2. The distinction between “Roadmapping” and “Roadmaps”

The distinction between roadmapping and roadmaps, which are often mistakenly viewed as interchangeable, is important. The term “roadmapping” refers to the process to develop a roadmap, whilst the term “roadmap” refers to the physical artefact produced from

60 For reference, Smith splits this question into two components: “what is stopping us from getting there?” and “what needs to be done to overcome the barriers?” (Smith, 2007).
roadmapping⁶¹. Both the process of creating a roadmap – roadmapping – and a roadmap itself have useful functions. Roadmapping is carried out by individuals from different functions of an organisation (or system) in order to build consensus towards a common goal (Phaal, Farrukh & Probert, 2010; Phaal, 2004; Zurcher & Kostoff, 1997). For instance, functions within an organisation or industry that are conventionally separated, for instance, marketing and as R&D, can be brought together in the roadmapping process to identify crossover needs, gaps, strengths and weaknesses (Albright & Kappel, 2003; Kostoff & Schaller, 2001; Phaal, 2004; Richey & Grinnell, 2004). Conversely, a roadmap, by displaying a “future view of the technological landscape” (Kostoff & Schaller, 2001), shows the steps an organisation needs to take to achieve its stated outcomes and goals and serves as a platform for debate and joint working (International Energy Agency, 2014; Winebrake, 2004; Phaal, Farrukh & Probert, 2010). Combined, both the process of roadmapping and roadmaps help to identify challenges and opportunities across organisations, sectors, or products by providing a visual structure on which to conduct strategic planning (Phaal, Farrukh & Probert, 2010). This allows roadmaps to inform decision-makers at all levels to make better decisions (Garcia & Bray, 1997).

3.2.3. Types of roadmap

Roadmapping has been adapted to many strategic contexts which vary in scope and format, and the method has been applied to support organisations, governments and industries, see (Kappel, 2001; Amer & Daim, 2010; Phaal et al., 2012; Phaal, Farrukh & Probert, 2010; Beeton, 2007). Kappel’s roadmapping taxonomy⁶² in Figure 3-8 defines the scope of a roadmap using two key criteria:

- **Purpose**: is the roadmap for an organisation or a sector?
- **Emphasis**: is the intention to understand the impact of long-term market trends or to determine a route to market for a product?

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⁶¹ In this thesis, the terms “process” or “roadmapping” are used interchangeably to describe or refer to the method of creating a roadmap. The terms “structure” or “roadmap” are used to describe or refer to the physical structure of the roadmap itself.

⁶² Also refer to Beeton’s taxonomy (Beeton, 2007).
An industry-level (or “sector-level”) roadmap may present an amalgamation of knowledge of leaders across a sector to provide a view of the industry landscape. Organisational roadmaps, on the other hand, might focus on evaluating and prioritising R&D projects to achieve specific business goals (Amer & Daim, 2010). However, the emphasis on “technology” in “Technology Roadmap” is often misinterpreted. Roadmaps do not necessarily focus specifically on technology. Roadmaps can detail the development of a specific product, hence “product roadmaps” (see Figure 3-8). Industry roadmaps and product roadmaps are thus not overtly focused on technology, but both are sometimes referred to – somewhat confusingly – as “Technology Roadmaps”, rather than simply as “roadmaps”. Additionally, while this misnomer presents a challenge within the research discipline of Technology Roadmapping, the term “Technology Roadmap” (and “roadmap”) is commonly adopted as an expression to describe any plan of the future (Phaal et al., 2012; Kappel, 2001). Despite widespread use, many such “roadmaps” do not actually yield a graphical roadmap. For example, the nuclear branch of the International Energy Agency – who have incidentally developed their own comprehensive roadmapping process that does yield graphical roadmaps, see (International Energy Agency, 2014) – have produced a “roadmap for nuclear energy” which provides an overview of the key challenges for the
future of the industry, but it does not present a graphical roadmap (Houssin et al., 2015). Whilst it is pious to suggest that any use of the word “roadmap” should be constrained to roadmaps only developed using a specific method, the differences should be acknowledged. Naturally, in this thesis, the use of the term “roadmap” refers specifically to roadmaps created through the methodological approach of Technology Roadmapping.

3.2.4. The Technology Roadmapping process

Many roadmapping frameworks and processes have been developed, and many are derived from practical application. Whilst no two roadmapping processes are the same, typically dependent on the application; all adhere to the same basic format. The general roadmapping process comprises of several key steps: scope and planning; roadmap development (structure and content); workshops; continuous development. Figure 3-9 collates the steps of a generalised process collated from several well-established roadmapping processes.

63 For further useful examples, refer to (Neilson et al., 2011; Bruzzone, 2010; Cardella, Decker & Klein, 2017).

64 In particular, refer to (Phaal, Farrukh & Probert, 2009) which distinguishes the different types of roadmaps.

65 In this thesis, “framework” denotes a theoretical roadmapping process, e.g. T-Plan (Phaal, Farrukh & Probert, 2001a), whereas “process” refers to a roadmapping process that has arisen as a result of implementation, e.g. the LEGO group process (Kerr, Phaal & Thams, 2017a, 2017b).

66 The way in which the specific aspects of each of the roadmapping frameworks and processes inform the process developed in this research is detailed in Chapter 4 (Table 4-3).

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67 The roadmapping steps outlined are the researcher’s own interpretation of the generalised roadmapping process. The process shares an intentional likeness with the process later outlined in
The implementation of roadmapping can be influenced by the maturity, size and culture of an organisation or sector. An established organisation or industry that has existing strategic planning practices in place will have different requirements than a start-up. In the former, roadmapping must be developed to complement existing practices. In the latter, a roadmap may provide a kick-start to strategic planning activities. Similarly, to ensure that roadmapping is suited to the application, the process is usually managed by a facilitator (or facilitators). Facilitators adapt the process to suit the application; compile, edit, and review the roadmap; manage logistics; and help to develop action and implementation strategies to carry out the actions shown in the roadmap (Keltsch, Probert & Phaal, 2011; Phaal, 2004; Phaal et al., 2012). The following set of questions have been outlined to support the implementation of roadmapping. Such questions are typically addressed in the planning phase (see Figure 3-9) but are of continual importance as the scope and purpose of the roadmapping activity, as well as changes in the external environment, can be accounted for. The questions are adapted from (Phaal, Farrukh & Probert, 2001a; Phaal et al., 2012; European Industrial Research Management Association (EIRMA), 1997; Garcia & Bray, 1997):

1. What are the aims and objectives of the roadmapping activity? i.e. what is the purpose of the roadmap?
2. What is the vision of the organisation?
3. What are the boundaries of the roadmap? e.g. what is the time horizon of the roadmap? *(typically, the time horizon is aligned with the vision)*
4. What is the current position of the organisation? i.e. “where are we now?”
5. What are the critical steps that are needed to achieve the future desired position (the vision)?
6. Which factors, internal or external, need to be considered? i.e. which parts of the organisation, or otherwise, need to be represented in the roadmap?
7. What are the key challenges or opportunities? To identify driving forces (at a high-level at this stage).
8. How will the roadmapping process be developed and implemented? i.e. who is in control of the process?
9. Who needs to be involved? e.g. management, marketing, manufacturing etc.

Chapter 4 as they were derived through literature review and practice. As such, the collated process in Figure 3-9 is a contribution of this research.
3.3. Applications of roadmapping

3.3.1. Roadmapping for engineering systems

Roadmapping is commonly applied to systems of large scale and complexity (Phaal, Farrukh & Probert, 2010). The scope of a roadmap can be made to reflect the boundaries of the system to which it is applied. A roadmap thus provides a view of a complex system, to see all elements simultaneously without losing overall context, i.e. it provides a systems-view. Large, complex engineering systems require organisation and understanding to ensure coordination in development (Murman & Allen, 2003). Roadmapping, as a method, has roots in the manufacturing, semiconductors, electronics, and aerospace industries (Kerr & Phaal, 2020). Even now, the most common application of roadmapping is to product-technology systems. Mapping and understanding a system using roadmapping can ensure that a technology is developed in an integrated fashion, with all such elements, processes and actors accounted for R&D, resources, logistics, external technologies (supply chains), manufacturing, customers etc. A roadmap can show that organisations do not exist in isolation – they are part of a bigger system of customers, suppliers, competitors, governments etc. The development of fusion technology, like all engineering systems, is subject to economic, social and commercial drivers that influence the design and performance (Murman & Allen, 2003; Mindell, 2002).

A fusion organisation is a complex system. As a fusion organisation grows, the technology being developed, the actors in the system (both internal and external), and the drivers on the technology expand, and the system becomes more complex. A roadmap can provide a lens on that system and to ensure that all elements, drivers, and actors in the system are considered as they evolve.

3.3.2. Roadmapping for innovation

As detailed in Chapter 2, innovation is dynamic. Regardless of the model of innovation, technology does not progress linearly from R&D to market. Instead, it is a process that develops over time, with iterations, testing and failure. However, all stages of the innovation

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68 The subsequent use of the term “systems view” in this thesis refers to the way in which roadmaps provide a holistic perspective of all the elements, actors, and drivers in a system. Refer also to the definition of “systems” detailed in 2.2.3.

69 Interestingly, Motorola was one of the earliest developers of both roadmapping as a method, and engineering systems as an approach, to technology and innovation management. See (Murman & Allen, 2003; Kerr & Phaal, 2020).
process must be considered to successfully develop technology for market. The process is complex and, in reality, can be difficult to manage. Roadmapping is inherently suited to help understand and manage the innovation process. Due to its explorative approach, it can be used to identify potential risks, challenges or opportunities, particularly when applied to the earlier stages of the innovation process when ideas are “fuzzy”, thus helping to understand the future innovation pathway (Fitzgerald, Wankerl & Schramm, 2011; Phaal, Farrukh & Probert, 2010). Stemming from the systems-view it provides, a roadmap can effectively show all stages of the innovation process in a time-based layered format, accounting for both the technical and commercial drivers (at the front-end and back-end of the innovation process, respectively). Roadmaps can thus help identify a route to take technology to market, supporting the management of the innovation process (Albright & Kappel, 2003; International Energy Agency, 2014; Kostoff & Schaller, 2001; Phaal, Farrukh & Probert, 2010; European Industrial Research Management Association (EIRMA), 1997).

3.3.2.1. Roadmapping for agile, lean and open innovation

To fulfil its intended purpose, roadmapping must be a continuous process and roadmap must be treated as living documents, constantly evolving as circumstances change. In this regard, roadmapping can support agile innovation. Requirements frequently change in a fast-moving agile innovation environment, and these changes can be captured through roadmapping. As a continuous and iterative process, roadmapping can be aligned with agile innovation cycles (see 2.5.4.2 and 2.5.7.1). By understanding potential future challenges and opportunities, a roadmap can help to devise a strategy for an optimal route forward as it is seen at a given moment in time. Roadmaps can, therefore, support the design of new technology or product to be developed in the next cycle. The cycle of building, testing and learning from new technology (in the laboratory) or a new product (in the market) can inform whether to “persevere” along the same trajectory or to “pivot” (see (Ries, 2011)). Following the build-test-learn cycle, if aligned appropriately, a roadmap can be updated with the results – new ideas or information – from the previous cycle. Accordingly, the next innovation cycle can then be planned via a continuous roadmapping process, with the support of the updated roadmap.

Also related to agile innovation is the emphasis that roadmapping places on people. Roadmapping typically involves bringing together people, perspectives and plans from conventionally distinct functions of an organisation or sector. In identifying crossovers and conflicts between these functions, roadmapping can be used as a tool to build consensus and confidence (Phaal, Farrukh & Probert, 2010). Roadmapping, therefore, enhances cohesion which can inform decisions over which, e.g. market routes, product features or technologies, should be pursued.
Roadmapping can also support lean innovation. The layered structure of a roadmap can be used to separate all the elements in an engineering system (test machines, key technologies, manufacturing processes, resources, e.g. workforce, etc.) into parallel streams (refer back to the layers in Figure 3-6 and Figure 3-7). It can also plot these alongside the phases of the innovation process (market, technologies, products), to account for the drivers from all the phases of the innovation process and to understand how they affect the different parts of an engineering system. This can support the generation of more efficient plans by determining the best route forward, thus avoiding time wasted on unnecessary activities allowing increased efficiency in allocating resource, i.e. reducing waste (refer to 2.5.5.1).

There is also a link between roadmapping both agile and lean innovation in that both emphasise visual management and communication (see 2.5.4.1, 2.5.5.1 and (Rigby, Sutherland & Noble, 2018; Gonzalez, 2014; Dybå, Dingsøyr & Moe, 2014; Schuh, Lenders & Hieber, 2011)).

Finally, as it provides a systems-view (see footnote 68), a roadmap can be utilised as a tool to explore aspects of the engineering system and to identify potential external collaborators to support internal development, or vice-versa, thus providing a tool for open innovation, see (Caetano & Amaral, 2011).

In summary, roadmapping is suitable for application to agile, lean and open innovation. In particular, whilst Technology Roadmapping has previously been developed to support agile innovation, in practice, the application has been mostly for software; solving problems that are short-term to match the pace of software development. The application of roadmapping for hardware-based agile innovation is accordingly considered as a key objective of this research (see 0).

3.3.3. Roadmapping for communication

The roadmapping process can support communication, e.g. via workshops, but a roadmap itself can also support communication as a graphical communication tool. Both aspects are detailed.

3.3.3.1. Communication in the roadmapping process

Typically, the roadmapping process includes workshops involving individuals from each function, including, for example, subject matter experts and managers. Workshops provide a space for individuals to communicate around a roadmap, to build consensus and converge on what the desired or expected future looks like for an organisation or sector (International Energy Agency, 2014; Phaal, 2004; Amer & Daim, 2010; Albright & Kappel,
The function to bring together important but disparate parts of an organisation or sector is a commonly reported psychosocial benefit of roadmapping, such as a sense of ownership and teambuilding, should also not be understated (Phaal, Farrukh & Probert, 2010; Albright & Kappel, 2003; Zurcher & Kostoff, 1997; Kerr, Phaal & Probert, 2012). Roadmapping workshops, therefore, place emphasis on human interaction and the co-creation of solutions using a roadmap as a visual centrepiece (Kerr, Phaal & Probert, 2012; Kerr & Phaal, 2015; Groenveld, 1997; Phaal, Farrukh & Probert, 2010; Dissel et al., 2009; Albright & Kappel, 2003; Zurcher & Kostoff, 1997; Amer & Daim, 2010; Garcia & Bray, 1997; Gersdsri, 2007).

### 3.3.3.2. Communications roadmaps

A roadmap is a visual artefact and can therefore also be an effective tool for communication (Kerr & Phaal, 2015; Amer & Daim, 2010; Kerr, Phaal & Thams, 2017a, 2017b; Kappel, 2001). A roadmap can be used to communicate a message of “here’s where we are going” by providing a view onto a complex system that is understandable to different audiences (Phaal & Muller, 2009; Albright & Kappel, 2003). Once a roadmap has been developed via a process like that outlined in Figure 3-9, it can be framed and structured to produce versions for the purpose of communicating with different audiences (Amer & Daim, 2010; Albright & Kappel, 2003; Kerr & Phaal, 2015; Kappel, 2001). Figure 3-10 provides an example of a roadmap developed for a public audience by NASA, which shows the key steps on the journey to Mars.

![Figure 3-10 NASA roadmap for the mission to Mars, reproduced under a Creative Commons license from (Ferguson, 2016).](image-url)
The NASA roadmap is an indication that careful design is required to ensure the graphical format suits the situation (Phaal, Farrukh & Probert, 2010). A single roadmap can spawn multiple roadmaps for communication, with different aspects emphasised, which are dependent on the needs and viewpoint of the audience (Dissel et al., 2009; Kerr, Phaal & Thams, 2017b; Kerr & Phaal, 2015). Figure 3-11 shows two visualisations of the same roadmap for the development of graphene technologies. The strategic view is intended for communication to funding bodies and politicians, while the tactical view is for an industrial (technical) audience (Kerr & Phaal, 2015).
Despite perceived usefulness as tools for communication, roadmaps for communication is often understated or overlooked, rather than considered as an integral part of the process (Dissel et al., 2009; Kerr, Phaal & Thams, 2017b; Kerr & Phaal, 2015). Due to the
effectiveness of roadmaps for communication but corresponding lack of emphasis in the literature, and due to the fact that communication is outlined as a key criterion for effective foresight (see 3.1.2), this research considers roadmaps for communication as a key objective (see 0).

3.4. Application of roadmapping to fusion start-ups

3.4.1. Criteria for roadmapping in fusion start-ups

The roadmapping method is comprehensively outlined in the previous sections of this chapter, but the method must now be considered for its application to fusion start-ups. New roadmapping processes – and roadmaps – are typically developed by adapting and combining existing frameworks, tools and structures to suit the given application. Although existing processes and structures could be used to inform the application of roadmapping to the fusion start-up context, fusion start-ups are somewhat unique. They are focused on hardware, are subject to many technical unknowns, come at a high cost and with a longer timescale to commercialisation. Accordingly, also referring to the analysis presented in Chapter 2, the following broad goals can be outlined for the application of roadmapping to the fusion start-up context:

- Yield both a roadmapping process and a physical roadmap
- Provide a systems-view of the fusion start-up engineering systems and the innovation process
- Relatedly, consider all stages of the innovation process simultaneously, to help guide technology commercialisation (technology to market)
- Provide a way to identify and characterise both the key technical and commercial challenges and opportunities on the path ahead
- Account for the agile, lean and open innovation principles that underpin fusion start-ups as outlined in 2.5.7. (also see 3.3.2.1)
- Support communication within a fusion start-up via workshops (or similar), and support external communication via the production of focused communication roadmaps

To the best of the researcher’s knowledge, no roadmapping process exists that is suitable for specific application to the fusion start-up context. However, several fusion roadmaps have been developed over the past 20 years, see (Phaal, 2011). The European fusion roadmap is the most recent and most relevant as it outlines the route to commercialisation for the public fusion programme in Europe and thus must be considered for application to fusion start-ups.
3.4.2. Existing fusion roadmaps: the European Fusion roadmap

The European fusion roadmap is an example of a sector-level roadmap (refer to Figure 3-8). It provides insights on the programme at a high level, detailing scientific milestones and broad technology development needs. Two iterations of the European fusion roadmap have been published, in 2013 and 2018. The latest version is shown in Figure 3-12.

![Figure 3-12 The European Fusion Roadmap (2018 version), reproduced with permission from (EUROfusion, 2018).](image)

High-level objectives, specifically for ITER and its satellite R&D programmes for DEMO, are well characterised. While roadmap shows the “what” and the desired “when”\(^\text{70}\), it does not incorporate the “how” – specifically, how to progress from technology to market. Furthermore, the cost of electricity (see “mission 7” in (Donné et al., 2017)) is outlined as a key driver, yet the roadmap does not definitively address “why” or “how” it will influence development. It is thus missing many of the features of an effective roadmap, as detailed in 3.2.1.

As detailed throughout Chapter 2 of this thesis, successful innovation requires the consideration of both technology-push and commercial-pull drivers. Criteria outlined in (Phaal, Farrukh & Probert, 2009) implies that the European fusion roadmap is a linear roadmap. Moreover, the European fusion roadmap can further be categorised as a

\(^{70}\) For unknown reasons, despite detailing precise dates in the previous iteration of the public programme fusion roadmap (see (Romanelli, 2012)), in the current iteration no dates are shown.
“technology sequence analysis”. A technology sequence analysis shows the technical steps required to reach the goal but takes a normative approach, yielding a roadmap that is of low complexity but which clearly defines steps to a desired future state. That the European roadmap is a characterised as such reflects the underlying linear model of innovation upon which the public programme operates, per analysis in 2.3. Reminiscent of the linear model, the European fusion roadmap determines critical technology gaps, but it does not consider commercialisation and is instead focused on the earlier stages of the innovation process.

In summary, the European fusion roadmap represents a roadmap that shows the trajectory for the existing fusion paradigm for the public programme, placing a sharp focus on the science and technology steps, i.e. the first stages of the innovation process. The roadmap does not account for commercial drivers and does not inform the development of successful innovation strategies. It is not useful as a foundation for the development of a roadmap for fusion start-ups. A suitable roadmap for a fusion start-up must instead be based on the principles as outlined in 2.5.7, and follow the roadmapping process as a method, as outlined in 3.2. Most critically, it must support innovation by incorporating the issues of “how” and “why”, which are not considered in the European fusion roadmap.

3.5. Research approach, questions and objectives

3.5.1. Research approach

Roadmapping is unique in that it is both a research method and a functional management tool, meaning it is of interest in both academia and industry. The roadmapping method has been extensively analysed in this chapter concerning the research problem. However, a suitable methodology through which to apply roadmapping as a research method must be identified. A suitable methodology must ensure that application to fusion start-ups is useful in the real-world. An action research methodology, in which the researcher is embedded in a real-world fusion start-up as a case study over a long period, is thus

71 The critique of the European fusion roadmap here is based only upon what is available in the public domain. However, there is no evidence that the roadmap was not produced by following a process similar to that described in 3.2.

72 Refer again to footnote 6 for the difference between the definition of “methodology” and “method”.

73 This is referred to as a longitudinal case study, which are carried out over periods of time long enough to see changes as a result of the actions of the research. See (Easterby-Smith, Thorpe & Jackson, 2012).
selected as a suitable method. Before the specific use of action research as a methodology and roadmapping as a method is detailed, the nature of this research as inherently interdisciplinary – the development of hardware-based technology in a social system (see 2.2.3) – must be discussed from the perspective of research ontology and epistemology.

3.5.1.1. Interdisciplinary research (ontology and epistemology, and positivism and interpretivism)

All researchers have a conception of reality that defines how they view the relationship between themselves and knowledge. This conception is defined by the terms: ontology and epistemology. Ontology is the “nature of being”, and epistemology is the relationship between the knowledge and the knowledge-seeker (or “the nature of knowing”) (Carson et al., 2001; Hudson & Ozanne, 1988; Willis & Edwards, 2014). There are two key philosophical dispositions about ontology and epistemology: positivism and interpretivism. Positivism is the belief that there is a single demonstrable objective truth that does not change, regardless of a researcher’s perspective. Interpretivism is the belief that there are multiple realities which are socially constructed, relative and ever-changing (Carson et al., 2001; Hudson & Ozanne, 1988).

Positivism tends to embrace research methods that allow the study of a problem in an objective way to identify (and measure) objective knowledge. By contrast, interpretivism perceives that knowledge is a social construct that evolves in, and is shaped by, specific contexts that are local to the problem being studied (Willis & Edwards, 2014). Differences across research fields that are positivist and interpretivist have spawned conflicting methods as well as worldviews, are a common barrier when disciplines collaborate and communicate. It is certainly not in the scope of this thesis to fully explore the differences between positivism and interpretivism. However, it is necessary to understand how the researcher interprets positivism and interpretivism in the context of this research – which explores fusion innovation management from an engineering systems perspective – as it embraces and employs elements of both.

In an isolated or controlled environment, positivism can thrive as a research approach. Naturally, research into the science of nuclear fusion has been dominated by positivist research methodologies. However, as in all engineering systems, upon real-world application, the problems that are grounded in natural science become coupled with – and

74 There are alternative philosophies beyond just positivism and interpretivism, including “post-positivism” and “critical theory”. These are not discussed here, as positivism and interpretivism are the two philosophies relevant thesis – and are perhaps also the two that are most obviously in contrast. See (Willis & Edwards, 2014; Hudson & Ozanne, 1988).
embedded in – social systems. Therefore, while fusion pertains to the development of technology that is grounded in physical science, bounded by single truths and natural laws, the broader engineering system in which fusion science exists must be acknowledged. It is a technology being developed in the real world, which is inhabited and influenced by humans.

Like the broader discussion around the elements, drivers, and actors in engineering systems, to ensure that both the technical and social aspects of fusion technology development can be captured, an interdisciplinary research approach is needed. This means embracing elements of both positivist and interpretivist philosophies and methodologies, which come from both natural and social science research (Lach, 2014). Willis and Edwards suggest that both positivist and interpretive research methodologies follow the same characteristics. They place emphasis on finding a solution to a problem; are field-based; and are iterative (Willis & Edwards, 2014). Action research as a research methodology, and roadmapping as a research method, together form an approach that is suitable for interdisciplinary research.

3.5.1.2. Action research using Technology Roadmapping in a fusion start-up case study

Kurt Lewin, a social psychologist who is widely regarded as the originator of action research, held that to drive change, solutions to real-world problems should be developed in that specific real-world context (Willis & Edwards, 2014). Rather than simply observing the behaviour of an organisation or system in a controlled setting, action research actively dissolves the barrier between the researcher and the research subject. Action research involves either:

- The study of a specific context to develop knowledge and understanding to inform action(s)
- The development and implementation of action(s) in a specific context, and the study of the impact(s) of the action(s)

Although action research originated in a social research field, and thus historically tends to interpretivism, it has since been applied to research fields that have traditionally been the subject of positivist research methods. Action research deployed in both interpretivist and positivist settings follows the same five broad steps, which are carried out iteratively (Lewin, 1946; Susman & Evered, 1978; Willis & Edwards, 2014)75:

75 Incidentally, action research is therefore akin to the “build-measure-learn” and “plan-do-check-act” from the agile and lean innovation paradigms, respectively.
1. Diagnosis (to identify the problem)
2. Planning (design of solutions to the problem)
3. Action (implementing the design)
4. Evaluation (reviewing the implementation)
5. Learning (capturing lessons and iterating the solution)

Roadmapping is a method that has been used to support problems in both engineering and social systems. It has utility as it can account for both human and non-human elements, drivers, and actors. The application of roadmapping through action research is thus suited to the study of systems in which humans and technology interface, and the method naturally allows for elements of both positivist and interpretivist philosophies. While a range of roadmapping frameworks exist to be readily applied to similar problems, adopting an action research approach allows the development of a functional roadmapping framework that is useful for a real-world fusion start-up. Through this approach, a solution can be developed in response to local problems identified by the researcher; the solution can then be implemented and iterated over time, following the five steps detailed above and the roadmapping process (see Figure 3-9).

Tokamak Energy Ltd, a UK-based fusion start-up pursuing a route to commercial fusion via the spherical tokamak and high-temperature superconducting magnets, agreed to be used as a case study for this research. The research presented in the next chapter is thus carried out with the researcher embedded in Tokamak Energy Ltd.

3.5.2. Research question(s)

Accordingly, the following two chapters will address Research Question 2 (see Table 1-1):

**Research question 2A**: Can an innovation management method be adapted to fusion start-ups – which operate on an agile innovation model – to support the commercialisation process?

**Research question 2B**: Consequently, how can the development and application of Technology Roadmapping support fusion start-ups?

Chapter 4 details the application of the roadmapping method Tokamak Energy as a case study, thus addressing research question 2A. Chapter 5 evaluates the effectiveness of the application of roadmapping detailed in Chapter 4, thus addressing research question 2B. Conclusions are collated in Chapter 8.
3.5.3. **Research objectives**

Three sets of research objectives to address research questions 2A and 2B – which specifically support planning, innovation, and communication in fusion start-ups – are outlined in Figure 3-13 based on the list in 3.1.2.

- **Research objective i: roadmapping to support planning**
  - Support planning by providing a means to identify and characterise future challenges and opportunities
  - Provide a holistic, systems-view of the company to connect disparate functions and align company needs
  - Embed roadmapping as a functional planning tool for the organisation

- **Research objective ii: roadmapping to manage innovation**
  - Develop a roadmapping process and roadmap that accounts for both commercial and technology drivers (and needs)
  - Develop a roadmapping process that encompasses the principles of agile and lean innovation, as outlined in 2.5.4, 2.5.5 and 3.3.1.1.
  - Develop a roadmapping process that encompasses the principles of open innovation, as outlined in 2.5.6.2.
  - Develop a roadmapping process and roadmap that considers all stages of the innovation process are considered, with reference to fusion in the context of the S-T-A-M model as outlined in 2.6.3.

- **Research objective iii: roadmapping for communication**
  - Develop a roadmapping process to facilitate internal discussion about the future
  - Develop a roadmap that supports internal communication across functions
  - Develop variants of the roadmap to communicate with different audiences, including external audiences

*Figure 3-13  Research objectives for research question 2 (2A and 2B).*

The research objectives guide the application of the roadmapping method in Chapter 4. Consequently, Chapter 5 will evaluate whether the roadmapping objectives were met.

3.5.4. **Bias and generalisability**

As with all action research, the research is based on the needs of the organisation (or system) under study, and the perspective of the embedded researcher in response to those needs, i.e. the local context. Whilst the method is applied to be useful for all fusion start-ups, specific actions and decisions are made to support the case study Tokamak Energy Ltd. The rationale behind the actions and decisions to develop the process specifically for the Tokamak Energy programme is explicitly detailed at every step, to ensure that the process can be repeated and also for generalisability. The ways in which the company and the researcher may have introduced bias or otherwise influenced the research is discussed as part of overall methodological reflections in section 5.1. The lessons, practice and theory
that can be derived from the context-specific application of roadmapping at Tokamak Energy Ltd to be broadly useful for all fusion start-ups, i.e. the generalisability, is detailed from section 5.2 onwards.

3.6. Chapter Summary

Potentially suitable Futures methods have been reviewed with reference to the 5 Cs (see Table 3.1). Technology Roadmapping is selected as the most suitable method for the application to fusion start-ups. The roadmapping method has been outlined with reference to the research focus; in particular, how the method could support planning, innovation management, and communication have been emphasised and informed the development of research objectives. Chapter 4 will detail the application of roadmapping to fusion start-ups using Tokamak Energy as a case study.

This chapter has, in part, answered research question 2A; Technology Roadmapping appears to be a method well suited to support fusion start-ups manage the innovation process. However, application of the method to the fusion start-up context is necessary, and thus the contributions from this chapter as well as Chapters 4 and 5 are collated in the conclusions with reference to the research question in Chapter 8.
Chapter 4. Developing a Technology Roadmapping process for Fusion Start-ups: Tokamak Energy as a case study

This chapter presents the application of roadmapping to a fusion start-up case study, Tokamak Energy. The research objectives detailed in 3.5.3 (for planning, innovation, and communication) are considered in the design, development and implementation of the roadmapping method.

Aspects of, and content presented in, this chapter can be found in part or whole in the following peer-reviewed publication, published in the journal Technology Forecasting and Social Change:

4.1. Defining Tokamak Energy’s vision and mission

It is necessary to outline the vision and technical mission of Tokamak Energy to provide context for the application of the roadmapping method\(^\text{76}\).

4.1.1. Tokamak Energy company profile

Tokamak Energy Ltd, formerly Tokamak Solutions Ltd, is a privately held company based near Abingdon, in Oxfordshire in the UK. Started in 2009 by a team of three entrepreneurial scientists, the company has seen significant growth in terms of investment, workforce and (international) recognition in recent years. The company’s profile is provided in Table X.

<table>
<thead>
<tr>
<th>Company name</th>
<th>Tokamak Energy Ltd (formerly Tokamak Solutions Ltd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Address</td>
<td>173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, UK</td>
</tr>
<tr>
<td>Date founded</td>
<td>2009</td>
</tr>
<tr>
<td>Founders</td>
<td>Dr David Kingham, Dr Mikhail Gryaznevich, Mr Alan Sykes</td>
</tr>
<tr>
<td>Chief Executive Officer</td>
<td>Mr Jonathan Carling</td>
</tr>
<tr>
<td>Total investment (est.)</td>
<td>£77 M (GBP)</td>
</tr>
<tr>
<td>Key investors</td>
<td>Legal &amp; General, Hans-Peter Wild (Rudolf Wild &amp; Co), Winton Ventures, Rainbow Seed Fund, Oxford Instruments.</td>
</tr>
<tr>
<td>Number of employees</td>
<td>~80</td>
</tr>
<tr>
<td>Company target</td>
<td>To demonstrate the feasibility of fusion as an energy source by 2030</td>
</tr>
<tr>
<td>Technical Achievements</td>
<td>Filed 40 families of patents, incl. on HTS magnets and spherical tokamaks; Only fusion company involved in the UK government Advanced Modular Reactor (AMR) programme; HTS magnets produced a magnetic field of more than 20 Tesla (2019); Built and commissioned ST-40 tokamak (began operations 2018); First tokamak (ST-25 HTS) to operate with HTS magnets (2015);</td>
</tr>
<tr>
<td>Accolades</td>
<td>“Disruptor to watch” in The Sunday Times Fast Track 100 (2019); identified as “one of three most promising innovative fusion concepts” by International Energy Agency (2017); dubbed “Technology Pioneer” by Davos World Economic Forum (2015); Winner of Future Planet Awards “Climate Change” category (2018).</td>
</tr>
</tbody>
</table>

Table 4-1 Tokamak Energy Ltd company profile as of June 2020 (information presented is available in the public domain).

\(^{76}\) In reality, the vision and mission of any organisation will change over time. A roadmap can be used as a tool to capture such changes at the strategic level.
4.1.2. Tokamak Energy’s vision

Tokamak Energy’s goal is to demonstrate the commercial viability of fusion energy by 2030 via the spherical tokamak with novel high-temperature superconducting (HTS) magnets (Sykes et al., 2015; Windridge, 2019; Costley, 2019). Figure 4-1 provides a schematic of a spherical tokamak concept with key technical systems labelled.

![Schematic of a spherical tokamak concept](image_url)

**Figure 4-1**  Labelled schematic of a spherical tokamak concept. Labels produced by the author; image of tokamak courtesy of Tokamak Energy Ltd.

Tokamak Energy’s technical approach via the spherical tokamak is based on promising results from previous spherical tokamaks experiments in MAST (at Culham Centre for Fusion Energy, UK) and NSTX (at Princeton Plasma Physics Laboratory, USA). More recently, through analysis of the most recent data using system codes, scientists at Tokamak Energy found that the fusion power gain (the critical parameter, $Q_{\text{fus}}$, see 1.1.1) is mainly dependent on the absolute fusion power as well as the energy confinement (the rate at which a plasma loses energy) and is only weakly dependent on the size of the plasma (Costley, Hugill & Buxton, 2015). In addition, this work showed that a high $Q_{\text{fus}}$ could be achieved at relatively low fusion power. The received wisdom was that increasing the plasma size and fusion power was necessary to increase fusion performance, especially fusion gain ($Q_{\text{fus}}$), and this was a large part of the scientific rationale behind the size of the ITER tokamak. Costley also shows that the influence of plasma shape is important. Specifically, increasing shape can result in a significant reduction of size and/or field for the same fusion performance (Costley, 2019). These findings open a possible route to fusion via smaller tokamaks.

Accordingly, Tokamak Energy’s approach is based on increasing the value of the physics parameters for plasma shape and magnetic field strength by way of using a spherical tokamak configuration and HTS magnets, respectively. Spherical tokamaks have a smaller
aspect ratio (the ratio of the major radius to the minor radius of the plasma), and higher
 elongation (ratio of vertical height to the minor radius) than conventional tokamaks. The
difference in shape between the two types of tokamak is shown in Figure 4-2. Most
importantly, the enhanced elongation yields a significant increase in the physics parameter
for shape, which is largely dependent on elongation over aspect ratio, over conventional
tokamaks (Costley, 2019).

![Comparison of conventional tokamak and spherical tokamak plasma shapes](image)

**Figure 4-2** Comparison of conventional tokamak and spherical tokamak plasma
shapes, reproduced with permission from (Peng, 2000).

Tokamak Energy’s approach is also focused on the development of HTS magnets which
show the potential to achieve higher magnetic fields and with greater efficiency than existing
low-temperature superconducting (LTS) magnets77. HTS magnets can achieve higher
magnetic fields and larger current density when cooled to approximately 20 K, when
compared to LTS which typically achieves lower fields and lower current densities and when
cooled to a much lower temperature (4 K). As such, the Tokamak Energy approach is very
different to the public fusion programme approach via ITER, in which increasing the overall
size of the machine is necessary as it is predicated on LTS magnets and a conventional
tokamak plasma shape. This is shown by the plot in Figure 4-3.

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77 Alongside other potential benefits, see (Bruzzone, 2010; Sykes et al., 2018), is the substantial
increase in cooling efficiency of operating HTS magnets at 20 K versus LTS magnets at 4 K (which,
incidentally, is discussed in Chapter 7).
Figure 4-3: Toroidal field ($B_T$) versus major radius ($R_0$) for constant fusion triple $nT_\tau E$ (Lawson Criterion), corresponding to $Q_{\text{LSE}} \sim 10$ for devices of different aspect ratio ($A$). The plot is derived from the Costley equation, which is shown in the figure from (Costley, 2019). Parameters: $H$ is a confinement enhancement multiplier, $q$ is the operational safety factor (typically $\sim 3$), and $\kappa$ is plasma elongation. The location of three reactors – the ITER reactor (see 2.1.2), Commonwealth Fusion System’s ARC reactor concept (see 4.1.4), and Tokamak Energy’s ST-E1 reactor concept (see 4.1.3) – are shown for context. Figure provided courtesy Dr Alan Costley.

In summary, there are two enabling – and disruptive – technologies that must be developed for Tokamak Energy’s approach to succeed: spherical tokamaks and HTS magnets. For further information, see (Costley, 2019; Windridge, 2019; Sykes et al., 2018; Menard et al., 2016) and (Tokamak Energy, n.d.).

4.1.3. Tokamak Energy’s mission

The Tokamak Energy programme must consist of building and operating a series of spherical tokamaks of increasing performance and, where necessary, carrying out parallel R&D on key tokamak components. Many of the technical challenges for Tokamak Energy are similar to those being addressed in public fusion programmes and solutions being developed in those programmes are intended to be used if the development is sufficiently advanced for the Tokamak Energy schedule. However, whilst the vision for Tokamak
Energy and some key technologies to be developed may be well defined, the milestones required are less so. As detailed in 2.6, milestones measure progress. Hence, the high-level requirements and performance criteria for all technologies must be identified to hit milestones.

The first milestone is the achievement of net power gain, i.e. $Q_{\text{fus}} > 1$, per the steps outlined in 2.5.7. The demonstration of this condition is thus critical to mission success for Tokamak Energy. Naturally, technologies that facilitate the realisation of this step, or indeed the next step, must be developed in parallel. Alongside plasma physics and HTS, other key technologies specific to the spherical tokamak approach are the inner radiation shield (for the central column of the tokamak) and the divertor\textsuperscript{78,79}. In addition to technology focus, another critical step is for Tokamak Energy to demonstrate that a private fusion company is capable of designing, building and operating fusion machines. This must be achieved through the build-up of a skilled team of experts, technicians and managers, as well as the development of a world-class facility.

After demonstrating $Q_{\text{fus}}>1$, i.e. net power production, the company must subsequently demonstrate net energy production. Net energy production is achieved by accounting for the energy consumed in the balance of plant such as for plasma heating and cooling. Net energy production is defined here as $Q_{\text{eng}} > 1$ (where “eng” is engineering gain). Net energy gain requires all core technologies to be sufficiently developed and integrated to demonstrate scalability to a next-step commercial fusion reactor. While precise engineering specifications of a reactor capable of such performance cannot be fully determined at this stage due to technical and commercial uncertainties, target high-level performance specifications can be identified, i.e. the tokamak must produce net energy; it must be feasible to build; as low cost as possible; safe and reliable in operation; and it must demonstrate scalability to a commercial product\textsuperscript{80}.

\textsuperscript{78} The central column of a spherical tokamak is thinner than on a conventional tokamak owing to the shape of the plasma, see Figure 4-2. A radiation shield must be designed to protect the magnets and components inside the column and thus the quantity of shielding dictates minimum device size. Similarly, space available to evacuate heat using the divertor dictates minimum device size as well as the maximum power of the device (based on how much heat the divertor can handle).

\textsuperscript{79} Other technologies require development but are not specific to the spherical tokamak approach. It is not expected that Tokamak Energy will carry out the required R&D for such technologies and will instead look to support from external partners. This notion is referred to later in this chapter.

\textsuperscript{80} Another important commercial performance criterion is the extraction of usable energy from the fusion reaction to produce electricity, or process heat for applications like hydrogen production or desalination, which are later discussed in Chapter 5.
The phases of the innovation process shown in the S-T-A-M model (2.6.2) can help understand the current position and required steps to commercialisation. By setting Tokamak Energy’s mission in the context of the S-T-A-M model, the path to achieving the company’s vision, i.e. “how we get there”, can be outlined. The current operating tokamak, ST-40, is advancing the understanding of several important physics and technical aspects. ST-40 effectively reduces the risk of some technical elements to enable the successful design and construction of next-step reactors; it is an early science and technology demonstrator (see Figure 2-12). The next planned device, ST-F1, is aiming to demonstrate net power gain ($Q_{\text{ fus}} > 1$). As such, ST-F1 represents the breakthrough MVD for Tokamak Energy (see 2.5.7.1). The device to overcome the T-A transition – Tokamak Energy’s MVP – will be ST-E1, which will follow ST-F1, overlapping in some phases. ST-E1 is intended to demonstrate the commercial viability of fusion energy. Of course, challenges will remain beyond ST-E1 for the full commercial rollout of fusion energy. Issues such as financing (for construction), international licensing, scaling up supply chains and the development of higher-performance materials to allow longer component lifetimes are all challenges to be considered, in addition to technological challenges.

4.1.4. The vision and mission of other fusion start-ups

As outlined in Table 2-1, a host of fusion start-ups are developing towards the goal of commercial fusion by means of novel physics concepts and disruptive technologies similar to Tokamak Energy. Many fusion start-ups share the same vision: to commercialise fusion on an accelerated timescale via a new reactor concept or disruptive technology. Many also share a similar mission trajectory to Tokamak Energy. For example, Commonwealth Fusion Systems, like Tokamak Energy, intends to develop HTS that will facilitate the realisation of $Q_{\text{ fus}} > 1$ in the “SPARC” tokamak, a conventional tokamak. The company will then demonstrate commercial viability in the “ARC” tokamak (Sorbom et al., 2015). Similarly, General Fusion is developing wholly novel non-tokamak technologies, such as acoustic drivers to compress a plasma in a pulsed fashion (as an alternative to magnets to confine a stable, continuous plasma) (Laberge, 2016). Both companies are developing key enabling technologies in parallel, which will later be built and tested into experimental reactors towards a commercial prototype81.

4.2. Producing a first-pass Technology Roadmap

Technology roadmaps are typically produced through a multi-stage process. For the application to Tokamak Energy, this is divided into three principal stages, with the latter two

81 For other examples, refer to Table 2-1.
stages carried out in parallel. The first stage, which is detailed in this section (4.2), outlines the scope and develops the basic structure to enable the production of a first-pass roadmap. The second and third stages involve the development of the roadmap. The second stage involved the addition of technical content, identification and characterisation of linkages, and development of the roadmap structure, which is detailed in 4.3. In parallel to development, the roadmap was reviewed through workshops, which is detailed in 4.4. Although occurring in parallel, development (4.3) and workshops (4.4) are detailed sequentially for simplicity.

Figure 4-4 shows the four steps to create a first-pass Roadmap. The steps are detailed in 4.2.1 through 0.

4.2.1. Step 1: Defining the scope and objectives for roadmapping

A roadmap is intended to give an overview of the entire development programme towards the defined goal and to be a tool to assist the management of the programme so that the technology is developed according to the agile innovation approach outlined in 2.5\textsuperscript{82}. Why the roadmap is being developed what the roadmap is expected to do, and how and who will be involved in the process must be determined. This activity must be carried out in close consultation with the senior management of the company. Table 4-2 outlines the key criteria to help determine the scope of the roadmap to be developed. It also determines the current position (or “where we are now”), which is required in the next steps of the process.

\textsuperscript{82} It is important to note that it is not in the scope of this research to determine or validate the technical feasibility of Tokamak Energy’s intended route to commercial fusion; this is not the focus nor the objective of deploying roadmapping in an organisation.
Figure 4.4  Process to develop a first-pass Technology Roadmap, derived from the Tokamak Energy application.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>For Tokamak Energy:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content: what is the scope and purpose of the roadmap?</td>
<td>The roadmap will be centred around the development of technology, but specifically, it must support development, innovation and communication:                                                                                              - Challenges, potential solutions, gaps in R&amp;D, or opportunities relating to technology development should be determined in the near-, mid- and long-term.</td>
</tr>
<tr>
<td></td>
<td>- It must determine the commercial needs to inform the required R&amp;D to support innovation.</td>
</tr>
<tr>
<td></td>
<td>- It must support communication, both internally and externally for the company.</td>
</tr>
<tr>
<td>Critical inputs: what information needs to be shown?</td>
<td>The following existing information must be integrated from existing company documents:</td>
</tr>
<tr>
<td></td>
<td>- Current concept designs.</td>
</tr>
<tr>
<td></td>
<td>- Current R&amp;D plans (or other documents containing potential solutions to address technology gaps)</td>
</tr>
<tr>
<td></td>
<td>- Strategic milestones (set by investors).</td>
</tr>
<tr>
<td></td>
<td>- Expected resource plans (from the business plan).</td>
</tr>
<tr>
<td>How will the roadmap be used?</td>
<td>The roadmap will be used to drive requirements for project planning. It will provide a high-level view of the desired future of the business, to identify potential business opportunities and to facilitate decision-making. It will drive the requirements of specific machines and projects by determining the required R&amp;D in order to facilitate agile innovation. It will inform the allocation of resource, thereby reducing waste, facilitating lean innovation. It will help to identify collaborators to facilitate open innovation. Specific derivations of the roadmap will be developed to communicate, e.g. project managers, investors.</td>
</tr>
<tr>
<td>Participation: who will be involved?</td>
<td>The development of the roadmap should be managed by a small team. However, key members of management must be involved in developing the process, and engagement with subject matter experts must be involved in developing technical content.</td>
</tr>
<tr>
<td>Resources: what are the constraints?</td>
<td>The company is constrained by the availability of workers, most of whom are focused on important technical activities. Funded by private investors, there is no scope for explorative R&amp;D, and the company must prioritise its funding of projects and activities.</td>
</tr>
<tr>
<td>What is the time horizon?</td>
<td>The structure of the roadmap must fit with the expected time to the target set by investors to demonstrate the commercial viability of the approach, i.e. 2030. Therefore, the time horizon of the roadmap will be approximately ten years.</td>
</tr>
<tr>
<td>Embedding the roadmap</td>
<td>The roadmap, and the process, will be developed to the point at which it can be considered an active tool that provides continuous support to the company.</td>
</tr>
</tbody>
</table>

*Table 4-2: Key criteria for the Tokamak Energy Technology Roadmap to support the development of scope, adapted from* (International Energy Agency, 2014; Smith, 2007; Phaal, Farrukh & Probert, 2010).
4.2.2. **Step 2: Review of existing roadmapping frameworks and processes**

Existing roadmapping frameworks and processes must be comprehensively reviewed as they may provide useful reference points in the application to fusion start-ups. Table 4-3 shows the key frameworks and processes used in the development of the process in this research. References are also provided throughout this chapter, where specific aspects of other frameworks and processes have been adopted or adapted.

<table>
<thead>
<tr>
<th>Function</th>
<th>Reference frameworks and processes</th>
</tr>
</thead>
</table>
| **To support the design of the roadmapping process** | - The Institute for Manufacturing (University of Cambridge) T-Plan (Phaal, Farrukh & Probert, 2001a)  
- European Industrial Research Management Association (EIRMA) roadmapping process (European Industrial Research Management Association (EIRMA), 1997)  
- Sandia National Laboratories roadmapping for strategic business development (Garcia & Bray, 1997)  
| **To support the structure/layout of the roadmap** | - Motorola roadmap (Willyard & McClees, 1987; Richey & Grinnell, 2004)  
- Lucent Technologies corporation roadmaps (Albright & Kappel, 2003)  
- Office for Naval Research guide to modelling roadmaps (Zurcher & Kostoff, 1997)  
- Guidelines for communications roadmaps (Kerr & Phaal, 2015; Kerr, Phaal & Thams, 2017b; Kerr, Phaal & Probert, 2012) |
| **To support the planning and organisation of workshops** | - The Institute for Manufacturing (University of Cambridge) T-Plan (Phaal, Farrukh & Probert, 2001a)  
- the LEGO Group roadmapping for management (Kerr, Phaal & Thams, 2017a, 2017b) |

*Table 4-3 Reference roadmapping processes and frameworks used to support development to the Tokamak Energy roadmapping process.*
4.2.3. Step 3: Determining roadmap structure

The current position of the Tokamak Energy development programme and the defined principal goal essentially define the boundaries of the roadmap; that is the start and “finish”\(^\text{83}\) both in technical content and time, and the S-T-A-M transitions define the major steps in the programme; the \(Q_{\text{fus}} > 1\) (the breakthrough MVD) and the \(Q_{\text{eng}} > 1\) (the MVP) milestones. These are presented at the top of the roadmap. As detailed in 4.1.3, the development through the devices; ST40, ST-F1 and ST-E1, and the parallel R&D on key technologies such as the HTS magnets, present the major elements of the development programme and collectively they plot a trajectory. It is possible to determine the current state of a particular technology and to – approximately – determine the desired future state of the technology required to achieve the company’s vision. Naturally, the required technology steps between these points plot a future trajectory, but that trajectory is as yet unknown and, therefore, is a central function of the roadmap. The required resources, i.e. the means to carry out technology development, must also be considered. Such requirements are unknown and thus must be factored in developing the structure – the “layers” (see 3.2.1 and 3.3.2) – of the Tokamak Energy roadmap.

Framing these considerations in the form of questions, and in the context of time, i.e. “where are we now?”, “where do we want to be?” and “how can we get there?”, by using a three-by-three matrix can help to determine a skeleton structure for the roadmap. The matrix can be adapted to suit a specific application. Typically, the layers of a roadmap, and thus the questions on the y-axis of the matrix, represent market, product and technology. However, given the primary focus of fusion start-ups on technology development, the questions for Tokamak Energy have been defined as shown in Figure 4-5. Accounting for commercial drivers – the “why” – is detailed in 4.2.4.4.

\(^{83}\)Roadmaps are never “finished”, but the mission and goals change over time. For now, “finish” refers to the perceived vision for Tokamak Energy at current.
Three-by-by matrix to determine the basic structure of a roadmap as per step 3 of the process. The questions on the y-axis can be adapted dependent on the scope of the roadmap being developed, adapted from (Phaal, Farrukh & Probert, 2010).

The matrix is then populated using the information detailed in 4.1.1 and 4.1.3 against criteria outlined in Table 4-2 to develop a completed matrix, as shown in Figure 4-6.

Three-by-three matrix to determine roadmap structure, filled in to reflect the mission and vision for Tokamak Energy.

Figure 4-5

Figure 4-6
4.2.4. Step 4a: Determining the layers of the first-pass roadmap

The layout of the information in the matrix structure naturally permits the definition of, and subsequently, the generation and organisation of content for, distinct roadmap layers. The layers shown in Figure 4-6 evolve to become the following:

- **Machines and Projects**: the devices and critical R&D projects that will demonstrate the technology that will be developed, as described in 4.2.4.2.
- **Technology Gap Issues**: areas of technology development in which there is considerable uncertainty and further development is needed, as described in 4.2.4.1.
- **Resources and Capabilities**: the support required to close the gaps, as described in 4.2.4.3.

Central to the roadmap for this application is technology development. Accordingly, identified Technology Gap Issues are described first, with the other layers of the roadmap described thereafter.

4.2.4.1. Technology Gap Issues

Inevitably there are specific challenges in technical understanding or in technology development, i.e. technologies at low TRLs (see 4.3.4), that must be overcome for Tokamak Energy to realise commercial fusion. These can be broken down into a number of specific Technology Gap Issues (TGIs). The TGIs were first identified by Dr Alan Costley at Tokamak Energy but modified and characterised as a collaborative activity between the PhD researcher and Dr Costley, as well as other staff at Tokamak Energy. Initially, 17 TGIs were identified. Over time, these were collated into 15 TGIs, which are further detailed in 4.3.2.

Even though ST-E1 will ultimately integrate all the TGIs, certain problems can initially be solved independently and in parallel. The approach enables some decisions to be deferred in order to make faster progress in the near-term. Accordingly, breaking up challenges into TGIs supports an agile and lean approach to technology development. This is also analogous to NASA’s Mercury and Gemini programmes in which challenges were developed in parallel but both to support the Apollo mission, see (McCurdy, 2001).

4.2.4.2. Machines and projects

Project pathways can be clearly illustrated in a Technology Roadmap format (Albright & Kappel, 2003). Tokamak Energy is developing machines of increasing complexity and performance for its development programme. These machines are aimed at overcoming
milestones and thus also, in some cases, aimed at resolving specific TGIs. In addition, there is in-house R&D on key components, for example, the HTS magnets (TGI #5) and on the radiation shield for the central column (TGI #7). The “Machines and Projects” layer details the machines for Tokamak Energy; ST-40, ST-F1, and ST-E1, and key current technology projects, such as for the divertor (TGI #6). ST-40 and associated R&D projects to inform and facilitate the design, and ultimately the build and operation of ST-F1. In turn, ST-F1 and future projects will support the development of ST-E1. Each machine and all projects progress the state of technology or understanding and thereby resolve or reduce the risk associated with specific TGIs.

4.2.4.3. Resources and Capabilities

Closely linked to the technical programme is the development of resources necessary to enable progress with the technical elements. The Resources and Capabilities layer is used to define the enabling resources required to realise the technology development envisioned. Significant financial investment; a workforce of professionals, designers, technicians and administrators; new facilities; various hardware; and, in some cases, novel materials (and natural resources) for which considerations regarding supply chain and specialised manufacturing processes, amongst other things, are necessary. The developments of these aspects are displayed in the lower layer of the roadmap.

4.2.4.4. Accounting for commercial drivers: Strategic milestones

As detailed in Chapter 3, product-technology roadmaps typically follow a layered format showing market, product and technology (see Figure 3-6 and Figure 3-7), which thus inherently connects product and technology development to commercial needs. In Chapter 2 of this thesis, the importance of commercially driven technology development in fusion is consistently emphasised, as without consideration of commercial drivers a roadmap would represent only a technology-push view of the desired future programme. However, the “why” is not explicitly defined – via a “markets” layer, or otherwise – in the matrix for Tokamak Energy in Figure 4-5. Despite this, it is not omitted from consideration in the development of the structure of the first-pass roadmap and the “why” is addressed by incorporating an additional layer showing “Strategic Milestones”. Strategic Milestones are defined based on the need to demonstrate performance to show progress towards commercialisation. Consequently, they are set and agreed between investors and company management and evolve over time. Although the structure of the roadmap remains

84 Challenges relating to the supply of such materials and natural resources are detailed in Chapter 6 and Chapter 7.
primarily focused on R&D, the strategic milestones serve to inherently tether the machine requirements and R&D to the commercial drivers. For example, the commercial viability of the ST-E1 machine dictates that it must generate power for a significant duration of time. Accordingly, technology R&D can be tied to that commercial need, by, e.g. creating a stable plasma that produces continuous fusion power or to develop materials that are capable of withstanding high heat and neutron loads. Therefore, strategic milestones inherently provide a view of the requirements for later stages of the innovation process, and in the context of the roadmap are considered to effectively represent commercial drivers.

It was decided by the company that a “markets” layer (see 3.2.1), which would be used to identify and account for commercial drivers for the company, would not be included in the first iterations of the roadmap and would be added later. To ensure that the “why” is accounted for, a layer detailing “strategic milestones” for the company, as agreed between investors and management, was integrated into the structure. The later introduction of an explicit markets layer and the associated challenges with doing this are detailed in 5.4.1.2.
4.2.4.5. **Generation of a first-pass roadmap**

Identifying the layers permits the generation of a first-pass roadmap structure, as shown in the schematic in Figure 4-7.

**Figure 4-7** Structure of the first-pass roadmap for Tokamak Energy (close-up of step 4 in Figure 4-4). Certain TGI’s are intentionally excluded as this diagram is for the representation of the overall roadmap structure only.

4.2.5. **Step 4b: Developing content for the first-pass roadmap**

Considerably more depth must be added to the roadmap in order for it to fulfil its intended purpose. In the first instance, content can be added to the first-pass roadmap, per Figure 4-8.
### Process to develop content for the first-pass roadmap for Tokamak Energy

**Figure 4-8**

<table>
<thead>
<tr>
<th>STRATEGIC MILESTONES</th>
<th>NEAR-TERM</th>
<th>MEDIUM-TERM</th>
<th>LONG-TERM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MACHINES &amp; PROJECTS</strong></td>
<td>MACHINE A</td>
<td>MACHINE B</td>
<td>PROJECT α</td>
</tr>
<tr>
<td>TECHNOLOGY GAP #1</td>
<td>TECHNOLOGY GAP #2</td>
<td>TECHNOLOGY GAP #5</td>
<td></td>
</tr>
<tr>
<td>TECHNOLOGY GAP #6</td>
<td>TECHNOLOGY GAP #7</td>
<td>TECHNOLOGY GAP #14</td>
<td></td>
</tr>
<tr>
<td>TECHNOLOGY GAP #15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>OTHER ENGINEERING PHYSICS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TECHNOLOGY GAP ISSUES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LOGISTICS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COMMERCIAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ORGANISATIONAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PROCUREMENTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It is important to ensure that the first-pass roadmap accurately reflects their view of the company, and thus the company’s vision and mission (see 4.1) must be plotted on the roadmap. The process to develop the content for the Tokamak Energy roadmap, following the steps as shown in Figure 4-8 is thus described. Strategic milestones were incorporated from the strategic plan, which contained targets set by and agreed with investors (denoted by “M1”, “M2” etc. in Figure 4-8). Existing concepts for future machines, as well as any R&D projects (e.g. the company’s existing HTS R&D programme), were derived from the company’s strategic plans and technology plans\(^85\). The TGIs were integrated into the roadmap, which informed – firstly at a high-level – the required R&D projects to close or solve the gaps identified by the TGIs. TGIs were characterised through analysis published research (e.g. academic research papers, scientific reports) as well as input from subject matter experts. For the first-pass roadmap, only several of the challenges could be mapped in a useful level of detail. However, analysis to further characterise the TGIs subsequently turned into a comprehensive activity and integral part of the process, which is detailed in 4.3.2. Finally, with support of company management, existing and future projections of the company’s resources and capabilities, e.g. manpower, capital, technical equipment, were translated into the roadmap\(^86\).

The procedure described thus far generates the first-pass roadmap. It is useful but incomplete, and further development is needed. Moreover, it is not necessarily coherent or integrated. Additionally, up to this point, many of the key staff within Tokamak Energy had limited involvement in its development. Closer involvement of key staff is required to improve the roadmap and – importantly – to generate a consensus.

\(^{85}\) Although the initial scope for next-step devices had already been outlined by Tokamak Energy, the ST-F1 and ST-E1 concepts evolved in part due to the development of the roadmap.

\(^{86}\) The resources and capabilities layer also included consideration of e.g. site location, engineering partners and media press releases.
4.3. Developing the Technology Roadmap

The next two sections detail the process of content development (4.3) and workshop review (4.4). The roadmapping process developed for Tokamak Energy depended on both expert judgement (through workshops) as well as the analysis of data and generating of roadmap. The process is shown in Figure 4-9. The square blocks indicate the development of the roadmap via various “input” activities, such as TGI analysis. The circular blocks indicate the development of the roadmap as a result of review workshops, which result in “outputs” such as action reports. As noted, in reality, the activities to develop the roadmap tended to more or less occur concurrently, but for simplicity, the process is described sequentially.

4.3.1. Technology Gap Issues

4.3.1.1. Characterising the Technology Gap Issues

For the Tokamak Energy programme, a total of 15 TGIs were identified. These were divided into three distinct categories: “physics”, “engineering” and “other”, in which the use of the word “technology” in “TGI” falls under the broad definition as described in footnote 10, i.e. that “technology” includes any and all hardware, processes (including manufacturing), software etc. Specific to the development of a roadmap for fusion start-ups, the word technology is taken to include materials and also extended to include scientific knowledge that must be acquired in the form of experimental data and system codes87. As a result, the scope, and thus the solutions to resolve the TGIs, are wide-ranging. Detailed descriptions of the 15 TGIs identified for Tokamak Energy are provided in Table 4-4. How the TGIs relate to components or technology systems in a future electricity-generating fusion power plant88, is shown in Figure 4-10.

87 Here, “system codes” are models used to predict the performance of future fusion machines based on existing data.

88 Although the power plant figure represents an electricity-generating power plant, other commercial applications are discussed in 5.4.1.2.2.
Figure 4-9  The roadmap development process, derived from application to Tokamak Energy.
<table>
<thead>
<tr>
<th>Type</th>
<th>Technology Gap Issue (TGI)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>#1 Energy confinement time</td>
<td>The scaling of the energy confinement time with device parameters, particularly size, field and shape, is a high impact element in the design of tokamak fusion reactors, see (Costley, 2019). The scaling for conventional aspect ratio tokamaks is well developed, but the scaling for spherical tokamaks requires further development and validation, see (Buxton et al., 2019).</td>
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<tr>
<td></td>
<td>#2 High gain and burning plasma physics</td>
<td>A high-gain plasma ($Q_{\text{ fus}} &gt; 3$) will incur self-heating (where the fusion plasma heats itself due to alpha radiation). Potentially as yet experimentally unseen plasma physics phenomena could occur and significantly affect plasma behaviour and performance (positively or negatively).</td>
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<td></td>
<td>#3 Plasma control</td>
<td>Long-pulse, steady-state plasmas are essential for a viable fusion reactor. Plasma ramp-up, ramp-down and control (for instabilities and disruption mitigation or avoidance) must be understood, designed for and, in the case of disruption mitigation, demonstrated. See (Gryaznevich &amp; Sykes, 2017).</td>
</tr>
<tr>
<td></td>
<td>#4 Auxiliary plasma systems (heating, current drive, fuelling and diagnostics)</td>
<td>Customised technology is required for heating, current drive (non-bootstrap fraction), fuel injection, and for making key in-vessel and plasma measurements (diagnostics) for burning plasma operation.</td>
</tr>
<tr>
<td>Engineering</td>
<td>#5 High-Temperature Superconducting (HTS) magnets</td>
<td>Development of HTS for practical use in fusion is limited. Technology must be developed in key areas: electromechanical design (stresses, joints, cables and connections), design for quench protection, design of cooling systems, design for use under neutron irradiation (including to understand the level of shielding required, which impacts device size). Additionally, the global supply of HTS tape is limited, and the performance of existing supply varies. Also see (Bruzzone, 2010).</td>
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<tr>
<td>TGIs</td>
<td>Engineering</td>
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<td>-----------------------------------------------------------------------------</td>
<td></td>
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<tr>
<td>#6</td>
<td>Exhaust power handling (Divertor)</td>
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<tr>
<td></td>
<td>Tokamaks must have sufficient power handling capability to handle the power</td>
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<tr>
<td></td>
<td>exhausted from the plasma (via the divertor). Although various divertor</td>
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<td></td>
<td>designs have been developed in public fusion programmes, a design suitable</td>
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<td></td>
<td>for a spherical tokamak must be developed, see (Costley, 2019).</td>
<td></td>
</tr>
<tr>
<td>#7</td>
<td>Inner radiation shield for the central column</td>
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</tr>
<tr>
<td></td>
<td>The geometry of a spherical tokamak necessitates a relatively thin central</td>
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<tr>
<td></td>
<td>column. A dedicated radiation (neutron) shield must be designed to protect</td>
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<tr>
<td></td>
<td>the HTS magnets in the central column, which in turn impacts minimum device</td>
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<tr>
<td></td>
<td>size. A functional design, materials capable of handling high heat loads and</td>
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<td></td>
<td>neutron loads, as well as an effective cooling mechanism, must be developed.</td>
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<td></td>
<td>See (Costley, 2019; Windsor, Morgan &amp; Buxton, 2015).</td>
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<tr>
<td>#8</td>
<td>Plasma-material interactions</td>
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<td></td>
<td>Plasma-facing and in-vessel components (e.g. the first wall) could be</td>
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<td></td>
<td>damaged due to energetic particle bombardment, in particular by a high fusion</td>
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<td></td>
<td>neutron flux which will limit component lifetime. Materials must be</td>
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<td></td>
<td>developed to achieve the desired performance.</td>
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<tr>
<td>#9</td>
<td>Fusion materials</td>
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<td></td>
<td>The development of fusion materials is essential for many components and</td>
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<td></td>
<td>systems. Structures inside a fusion reactor will be subject to high fusion</td>
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<td></td>
<td>neutron flux and high heat loads, as well as thermal ramping (causing</td>
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<td></td>
<td>fatigue) and large temperature gradients (inducing stress), which may limit</td>
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<tr>
<td></td>
<td>operational lifetime. Suitable materials must be selected, developed</td>
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<tr>
<td></td>
<td>through R&amp;D and qualified for use in the fusion environment. #TGI 9 Underpins</td>
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<td></td>
<td>many of the other TGIs, particularly #6, #7, #8, #10 and #11.</td>
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</tr>
<tr>
<td>#10</td>
<td>Remote handling and maintenance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Components (e.g. divertor, first wall, blanket) in a D-T fusion reactor will</td>
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<tr>
<td></td>
<td>become radioactive after reactor operation due to neutron irradiation.</td>
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<td></td>
<td>Repair and replacement must be carried out by remote handling. Dedicated</td>
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<tr>
<td></td>
<td>technology must be developed for the spherical tokamak.</td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Description</td>
<td>Details</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>#12</td>
<td>Tritium breeding and self-sufficiency</td>
<td>Fusion reactors must breed tritium via a lithium-based breeding blanket. A blanket must be designed to produce more than one tritium atom for every neutron produced by the fusion reaction and to extract the produced tritium effectively. A dedicated blanket design for a spherical tokamak is required, as, in particular, a spherical tokamak does not permit breeding in the central column due to space restrictions, thus impacting minimum device size. See (Menard et al., 2016) and Chapter 7.</td>
</tr>
<tr>
<td>#13</td>
<td>Energy generation</td>
<td>The blanket described in TGI #11 must transfer neutron energy to thermal energy, which can be converted into useful electrical energy or other process heat applications. The tritium breeding blanket and energy generation mechanism are thus inherently linked. For applications such as hydrogen production, new ex-vessel systems must also be developed.</td>
</tr>
<tr>
<td>#14</td>
<td>Economics of fusion for energy</td>
<td>While relatively small spherical tokamak reactors may be technically feasible, for the commercialisation of fusion they must also be commercially viable. Assessments of the commercial feasibility of spherical tokamak power plant, possibly through a modular approach, is required to optimise performance parameters, especially as regards the power and size, see (Chuyanov &amp; Gryaznevich, 2017). Although electricity generation is a key focus, the economic viability of other commercial pathways should be considered.</td>
</tr>
<tr>
<td>#15</td>
<td>Licensing, regulation and safety</td>
<td>The location of a suitable site, the development of a suitable regulatory framework, and securing necessary construction, operation, and decommissioning licenses represents a lengthy, multi-stage process. Engaging with regulators at an early stage will ensure that fusion systems are designed appropriately to follow procedures, thereby ensuring the end product – i.e. the ST-E1 reactor – can be built and operated.</td>
</tr>
</tbody>
</table>

Table 4-4  Definitions of the Technology Gap Issues (TGlIs) for Tokamak Energy.
Figure 4-10  Tokamak Energy TGIs representing systems in a fusion electricity-generating power plant, adapted with permission from (National Fusion Research Institute of South Korea Website: www.nfri.re.kr/eng/index, 2019). The tokamak shown is a conventional aspect ratio tokamak (South Korean’s K-DEMO) as an illustration of a spherical tokamak power plant does not exist.
As shown in Figure 4-10, each TGI typically represents the technology development challenges for a system in a fusion reactor, e.g. the tritium breeding blanket. Collectively, the TGIs define all technologies that must be developed to achieve the vision; all are crucial to the mission and must be resolved. For clarification, however, all TGIs vary and will not be resolved with a single solution at a single point in time. For example, for Tokamak Energy, TGI #1 (energy confinement time) requires that a certain level of plasma performance must be achieved, as well as a corresponding understanding of the physics, to be confident that the required net power gain can be achieved. Conversely, TGI #9 (fusion materials) requires the characterisation of the performance of existing materials in as yet unexplored ranges and possibly the development of new materials. Technology to resolve a TGI is thus developed over time. It is built and tested iteratively – via agile innovation cycles – and over time, the likelihood that the technology will succeed is increased, and the risk of failure is reduced. TGIs inherently relate to Technology Readiness Levels (TRLs), which are detailed in 4.3.4.

Although resolving all TGIs is essential to achieving the vision, for Tokamak Energy there are several TGIs that have a high impact on the spherical tokamak design, and thus on the feasibility of the company’s foreseen path to commercial fusion. Such TGIs are defined as “high-leverage”. Four TGIs have been identified: #1 (Energy confinement time), #5 (HTS magnets), #6 (Divertor) and #7 (Radiation shield for central column). It is necessary to further delineate TGIs, particularly those that are high-leverage, into a set of distinct issues, to represent the specific challenges or indeed the specific subsystems within that TGI. Hence, TGIs can be separated into several sub-TGIs within that TGI, similar to that described in (Phaal, 2004). For example, for TGI #9 (fusion materials), sub-TGI #9.1 could be the “first wall”, and sub-TGI #9.2 could be the “vacuum vessel”.

While all high-leverage TGIs and other TGIs that must be developed to deliver near-term goals are well characterised, somewhat naturally, TGIs that are critical later in the development programme are less developed. Some seemingly longer-term TGIs can have an impact on the near-term (refer to the example in 4.3.2.2), so it is important to consider them; to successfully manage innovation, one cannot just focus on the challenges of today but those that relate to future development, and also market deployment (refer again to Figure 2-14)\(^89\). Crucially, then, that all TGIs that have been identified (as shown in Table 4-4) and included in the roadmap ensures that even issues that are far in the future are still in scope. TGIs may be raised to “high-leverage” in the future, and it is possible that other TGIs may arise. However, in general, the number should reduce as technology development resolves open gaps.

\(^{89}\) Refer to (Freeman & Engel, 2007).
4.3.1.2. Determining TGIs for other fusion start-ups

Although each TGI was defined specifically (and independently) for Tokamak Energy, unsurprisingly there are significant overlaps with previously defined gaps from other fusion programmes, for example (Donné et al., 2017; Federici et al., 2016; Zarnstoff & Goldston, 2017). Further, whilst many of the TGIs developed for Tokamak Energy are directly transferrable to other non-tokamak based approaches by other fusion start-ups, the same method can be applied to yield new TGIs. Examples of TGIs for other fusion start-ups could be the development of plasma liners; fuelling, exhaust and energy generation systems for non-tritium fuel cycles; and improved understanding of concept-specific plasma physics.

4.3.1.3. The role of the researcher in developing the TGIs

Due to the nature of this action research with the researcher embedded within the organisation, the role of the researcher in developing the TGIs must be clarified.

In Summer 2016, Dr Alan Costley – technical consultant to Tokamak Energy and the industrial advisor for the research presented in this thesis – was tasked with identifying technical gaps relevant to the Tokamak Energy programme. The company perceived that characterising these gaps was central to developing a robust technology development strategy. As a result of this analysis, Dr Costley identified and broadly characterised 17 TGIs. Importantly, neither Dr Costley nor Tokamak Energy had dominion over the TGIs, as they represent technical gaps that are well characterised in the fusion literature. While specific TGIs may vary across fusion programmes, they represent challenges that are grounded in natural science. Each of the TGIs identified by Dr Costley was thus done so objectively, based on published scientific knowledge and support from subject matter experts inside and outside of the company. The only subjectivity introduced was by Dr Costley in judging which gaps are relevant to, and impact the Tokamak Energy programme. Whilst TGIs relate to problems that are fundamentally technical and scientific in nature, they interrelate and interact with other aspects in the overall engineering system – human and non-human drivers and actors. The researcher, supported by Dr Costley, determined that TGIs relate to specific technologies or components in the conceptual fusion reactor under development at Tokamak Energy. Together with Dr Costley, the researcher’s role was to adapt and contextualise the TGIs, to provide an integrated, systems-view of the overall engineering system. The TGIs could then be analysed with respect to one another, and to the technical and social elements, drivers and actors in the engineering system. To achieve this, the researcher had to gain a fundamental understanding of each of the TGIs. The TGIs were condensed from 17 to 15, and the TGI descriptions as detailed in the table were developed as a result of the collaboration between the researcher and Tokamak Energy.
Whilst the existing TGIs were adapted, the researcher did not dispute them. The researcher contextualised the information to be translated into the roadmap – determining how they interface with other aspects of the engineering system – and thus, the researcher was the integrator, not the originator of the TGIs.

4.3.2. Developing the TGIs

Since the TGIs are critical to Tokamak Energy’s development programme, they are necessarily the subject of deeper investigation. Ultimately, defining what is required in terms of R&D for TGIs informs the requirements of machines and projects. In turn, having an understanding of the required R&D permits an estimation of the resources required. To better understand the TGIs, specific questions must be addressed:

- What are the specific challenges to be overcome to resolve the TGI, and what are the potential solutions to resolve these challenges? (TGI analysis, 4.3.2.1)
- Does the development of this TGI affect other TGIs and, if so, how? (linkage grids, 4.3.2.2)
- What are the preferred means to resolve the TGI? (methods of resolution, 4.3.2.3)

4.3.2.1. TGI Analysis

Each TGI must be continually developed over time to develop a deeper technical understanding, to capture new ideas or knowledge that may result in the resolution of that TGI and to monitor progress on the R&D programmes to solve that TGI. Dedicated TGI analysis; an assessment of the current status of technology, was carried out as an important part of the roadmapping process for Tokamak Energy. A similar technique was used at Motorola, see (Richey & Grinnell, 2004). Typically, this involves a review of the status of the topic more broadly in public tokamak programmes, and then the determination of its expected importance to the internal programme. TGI analysis is thus largely an analysis and review exercise in which relevant external documents, particularly journal articles and reports from national laboratories, as well as the views and ideas of subject matter expert consultants, are gathered and analysed.

A library of content developed from the TGI analysis was created. “TGI files” were used to capture and collate information on the challenges, potential solutions, and other important information relating to specific TGIs. The format of information in the TGI files was suitable

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90 Despite this, the researcher does have subject matter knowledge in two key areas: fusion fuels and tritium breeding blankets, developed through separate research which presented in Chapter 6 and 7 of this thesis.
to be translated into the roadmap. Behind each TGI, there is a set of documents that provide
details of the challenges and potential solutions in greater depth\textsuperscript{91}. For an example of a
template for a TGI file developed for Tokamak Energy, see Appendix A-1 (for TGI #12).

TGI analysis can also be used to understand where existing R&D outside of the company
can support internal activities, and where there is no R&D, and thus an internal development
programme is needed. Internal R&D programmes naturally present an opportunity to
develop IP; TGI analysis supported the identification of R&D gaps, thus enabling an
understanding of IP opportunities. In some cases, however, collaborative R&D
programmes may be favoured over internal R&D programmes, due to cost or lack of
expertise. For instance, a separate company specialising in tritium handling systems could
carry out external R&D (either collaboratively or independently) in parallel to Tokamak
Energy’s internal programmes. Such an approach leverages existing expertise, equipment
and know-how, and saves time. It also aligns with the innovation organisation model to
utilise networks to develop technology more efficiently (see 2.5.1). In fact, the identification
of whether to develop specific technologies in-house or through external collaboration or
outsourcing formed an important part of the roadmapping process; see 4.3.2.3.

4.3.2.2. Linkage grids to determine TGI interdependencies

The generation of content for a roadmap can be substantially strengthened through the use
of management tools, and roadmaps can act as “integrating hub” to interface with other
technology or innovation management tools (Phaal \textit{et al.}, 2012; Kerr, Phaal & Thams,
2017b). Linkage grids are an effective tool that is commonly adopted to identify
interdependencies and integrate the layers of a roadmap (Phaal, Farrukh & Probert, 2005,
2001b; Phaal \textit{et al.}, 2012). For fusion start-ups, many of the technical aspects of TGIs are
inextricably linked, and these linkages have to be captured. For example, for the Tokamak
Energy spherical tokamak design, the divertor (TGI #6), the radiation shield for the central
column (TGI #7), and access for diagnostics and heating beams (TGI #4) all require space
and thus can affect the ability to breed tritium (TGI #12) as well as the ability to carry out
remote handling (TGI #10). All must be considered simultaneously. Linkage grids can
facilitate the understanding of high-level dependencies across these TGIs, to ensure that
disparate and parallel technology development streams will be developed with integration

\textsuperscript{91} It is noted that it is not possible for all TGIs to be characterised to the same level of depth. As a
fusion start-up progresses and expands its capabilities, and the corresponding roadmap is
developed, all the issues will become better characterised. Furthermore, as detailed in 4.3.1, in
some cases the TGIs can be further broken down into sub-TGIs. TGI files for TGIs in which sub-
TGIs had been identified, for example high-leverage TGIs, the same approach was taken as for TGIs
as described here, only with a greater depth of analysis.

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in mind. A simple schematic of a linkage grid used to understand the connections across TGIs is provided in Figure 4-11. Linkage grids were further employed with the purpose of integrating the disparate layers of the roadmap, see 4.3.3.

![Diagram of a linkage grid](image)

**Figure 4-11** A representation of a Technology Gap Issue linkage grid (red dots denote linkages).  

4.3.2.3. Identifying methods of resolution

For Tokamak Energy to progress towards a point where ST-E1 can be designed and built with confidence, a solution path needs to be identified, and a strategy developed to resolve each TGI. As alluded to, various methods of resolution are possible: Technology R&D can be carried out either in-house or externally. In-house, it can be carried out either through integration in one of the tokamak machines or via a dedicated parallel project. Externally, it can be carried out through collaboration, or via a “watching brief”; whereby technologies developed in existing R&D programmes are monitored and evaluated to then be brought in-house at a later time when the technology is ready or when needed. Through determining

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92 The linkage grid developed for Tokamak Energy accurately characterises the linkage between TGIs but is not provided here for reasons of commercial confidentiality.
the best strategy for technology development through a method of resolution, fusion start-ups can avoid reinventing the wheel\textsuperscript{93}, see (Fitzgerald, Wankerl & Schramm, 2011).

In certain cases, principally due to cost, it is only feasible to develop technology in the domain of public fusion laboratories that have access to specialist equipment and subject matter experts. Fortunately for fusion start-ups, some of the required technologies have already been developed for public programmes, see (Costley, 2019). Other technologies may arise from future as-yet-unknown developments in one of the numerous external R&D programmes supporting public fusion efforts (such as ITER), or even from other industries\textsuperscript{94}. External R&D can be leveraged by fusion start-ups if accessible and available on the needed timescale via collaboration, licensing or purchasing agreements. For R&D that necessitates external collaboration, fusion start-ups can create an innovation orchard; an innovation ecosystem in which private companies seek a network of collaborations with universities, industry, and government laboratories to leverage expertise, equipment or ideas to support inbound innovation on technology development (Singer & Bonvillian, 2017). The innovation orchard is aligned with the emphasis in the innovation organisation model on networks (Bonvillian & Weiss, 2015). From the perspective of fusion start-ups, inbound innovation from collaborators in their innovation orchard can yield significant value at relatively low cost. From the perspective of potential collaborators, fusion start-ups should be viewed as “industry” stimulating new R&D or utilising existing knowledge and expertise, rather than as competition.

Specifically related to the physics TGIs for Tokamak Energy, much useful and relevant information can be extracted from the programmes of upcoming spherical tokamak experiments such as MAST-U at Culham Centre for Fusion Energy, UK, and NSTX-U at Princeton Plasma Physics Laboratory, USA. For other TGIs for Tokamak Energy, for example, the development of HTS magnets (TGI #5), dedicated in-house R&D is needed due to the lack of relevant external developments, but also due to the fact that the HTS magnets are central to the company’s approach. All areas in which new technology is needed, or indeed where there is a new application of existing technology, there is an opportunity for the company to develop IP. For Tokamak Energy, the development of HTS magnets represents a key area to develop IP. Such an approach appears to present “closed innovation”. However, open and closed innovation are not necessarily mutually exclusive; the two can be combined. Certain aspects of an internal development programme may

\textsuperscript{93} Similar to the “make or buy” decision tool used in (Albright & Kappel, 2003).

\textsuperscript{94} It is particularly important for non-tokamak fusion approaches to explore potential solutions from outside of the mainstream public fusion programmes, as some overlaps exist other research sectors – such as the space sector – from which to leverage relevant technologies.
benefit from external support, whilst other aspects must be closed to protect IP. Further, not all technology development within a single TGI has just one method of resolution. Individual R&D needs for specific technologies within a TGI might be met by different collaborators or a mixture of in-house development and collaboration. For example, Tokamak Energy works with HTS manufacturers to collaboratively improve the performance of HTS magnetic tape. This represents an open approach to innovation in what is an otherwise closed part of Tokamak Energy's programme for the protection of IP. By reviewing all identified R&D gaps and subsequently recognising appropriate methods of resolution, the roadmap can support Tokamak Energy in identifying external opportunities identifying technology development opportunities to build up its IP portfolio and to further understand the gaps in its internal capabilities.

4.3.3. Using linkage grids to integrate the roadmap

Many aspects of the future development plan are interlinked and could impact other areas if new challenges arise, problems are solved, or there is a change in company strategy; all of which can occur naturally as a company progresses. Necessary changes must be captured in the roadmap for it to remain coherent and integrated. In addition to links between technical issues, i.e. between TGIs as detailed in 4.3.2.2, linkage grids can integrate all the layers of a roadmap. Because of programmatic priorities, linkage grids permit different layers of the roadmap to effectively “push” and “pull” one another. For example, the commercial “pull” of strategic milestones (set by investors) can be used to set target performance criteria for machines, which – in turn – informs R&D projects and technology development planning. In the opposite direction, newly discovered limits of technological capability, a slower than expected rate of development or technology breakthroughs can all “push” the technical requirements or the timescales to meeting milestones via machines or R&D projects. A consequence is that this can impact the ability to achieve strategic milestones on the intended timescale. In effect, linkage grids are thus used to quantify what is an already inherently complex connected system. The linkage

95 Longer-term TGIs are typically denoted broadly as “watching brief”, but aspects of the development can be brought in-house or become the subject of a collaboration at an appropriate point in the future.

96 Perhaps obviously, like the process of roadmapping in general, linkage grids must be continuously updated to be useful. New linkages, technology breakthroughs or changes to company milestones may cause some linkages to be obsolete, whilst others merely need updating.
grids for the roadmap developed for Tokamak Energy, and how they interact and integrate the layers, is shown in Figure 4-12.

Figure 4-12 Linkage grids to connect layers of the Tokamak Energy roadmap, adapted from (Phaal & Muller, 2009).

For fusion start-ups, the linkages between TGIs and machines are critical. They enable experimental programmes to be aligned to address key technical challenges. Particularly important is the development of TGIs related to longer-term activities. Uncertainties in the long-term can have an impact on current and planned near-term technology developments and designs. For example, although tritium breeding is not required for ST-F1, it will be essential for ST-E1. Early-stage solutions in all TGIs related to this issue for ST-F1 that can be extrapolated to ST-E1 are favoured; refer to 2.5.7.1. Similarly, the development of a solution for TGI #7 (radiation shield for the central column) is critical for ST-F1. However, various performance criteria mean that the radiation shield must be judiciously designed to be compatible with other technologies.

Linkage grids to evaluate the resources and capabilities required to develop TGIs effectively allows for the “resource-loading” of the technology programme. The function of the linkage

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97 For Tokamak Energy, the linkage grids that were developed were used both as a tool to generate content for the roadmap and as a reference tool to be used in workshops, see 4.4.2.

98 Even though there is no explicit linkage grid between e.g. Strategic Milestones and Technology Gap Issues, the two are linked inherently via linkage grids to Machines and Projects.
grid in this regard is not to produce a detailed account of the exact cost, hardware or workforce requirements etc. Instead, it provides the high-level criteria and the boundaries, with linkages to other key issues explicitly understood, to facilitate traditional engineering project planning (i.e. R&D or technology management, see Figure 2-14) via, for example, Gantt charts99. Continuing with the previous example for the required solution to TGI #7, resource-TGI linkage grids can help to identify key resource considerations to deliver the technology, e.g. recruitment of specialist materials engineers, or identification of potential suppliers for mechanical components (supply chain). Finally, it may be realised that there are barriers in the technology development or resources that means TGI #7 will impact the capability for Tokamak Energy to achieve its strategic milestone(s). As a result, the roadmap – interconnected by linkage grids – can indicate whether more investment and/or time may be needed to resolve the challenge, or whether other solutions should be sought. In summary, the roadmap thus provides a means to understand what is required for the solution to be practicable and can, therefore, function to “stress test” whether current plans or goals are viable. If they are not, then the roadmap can be used to assist the development of plans and realignment of goals that are.

4.3.4. Using Technology Readiness Levels as a metric for development

Technology Readiness Levels (TRLs) were originally developed by NASA for the purpose of assessing space technology (see (Mankins, 1995)). TRLs provide a metric to measure the progress of technology development, displaying technology maturity – or “readiness” – on a scale of 1 to 9, where TRL 1 represents a technology for which only basic principles are understood, and TRL 9 represents a technology that has been fully demonstrated in the environment for which it is intended, with the steps between showing progress. TRLs fundamentally provide a way to measure the reduction of risk; the closer you get to TRL 9, typically, the lower the risk that the technology will fail. TRL scales are application-specific; Figure 4-13 shows the scale with generic TRL steps.

99 The key differences between roadmapping and traditional project planning are discussed in 5.6.1.3.
TRLs are time implicit, but they provide a quantitative means of assessing the state of technology development. TRLs combine well with roadmapping as they can be used to assess the current position and a given future position, and have consequently been used as a supporting tool for roadmapping, see (Phaal, Farrukh & Probert, 2010; Dissel et al., 2009; Ilevbare, Probert & Phaal, 2014; Whalen, 2007). Unlike TRLs, roadmaps are time explicit and typically provide a qualitative view of the desired future. Hence, in applying TRLs to a roadmap, it is possible to create a roadmap that is both qualitative and quantitative. By first determining the TRL for the current state of a given technology, then comparing it with the TRL for the desired future state of that technology, TRLs can support the required technology development steps between the two positions. Combined with a roadmap, which may already have some steps outlined, TRLs can become a powerful tool to support planning, as well as monitoring, the development of technology.

For Tokamak Energy, TRLs were used to determine the desired future position for ST-F1 and ST-E1 and then compared against the TRLs for all TGIs at the current time. However, in attempting to integrate with the roadmap as well as to adapt across the different TGIs, several problems manifested. Firstly, it was determined that TRLs could not be applied uniformly across all TGIs. Secondly, judging the TRL for a future device, e.g. ST-F1 is a subjective exercise, typically requiring expert analysis, preferably from multiple persons to obtain consensus. Furthermore, and crucially, it requires a detailed concept or at least a good understanding of the specifications of that future device, as well as evidence to back up judgements. However, even if solutions could hypothetically be found to the above challenges, to introduce System Readiness Levels (SRLs) – which could integrate TRLs for all introduced TGIs – may result in further issues. Although the use of TRLs is important for developing a coherent and robust roadmap, the problems with integration were not
definitively resolved in the course of this research. The problems, as well as potential solutions associated with the implementation of TRLs, are discussed in 5.3.5.

4.4. Reviewing the Technology Roadmap through workshops

4.4.1. Overview of the roadmapping workshop approach

It is natural that key staff in an organisation have different knowledge, experiences and external contacts and, quite likely, different views on priorities as regards the future path. Potentially this can bring different content and perspectives to the roadmap. Whilst aspects were guided by company management, and specific technical information obtained through consultation with subject matter experts, the majority of the content developed described thus far was carried out by the researcher\(^{100}\). Several existing roadmapping processes make considerable use of workshops to create as well as review content, e.g. T-plan (see (Phaal, Farrukh & Probert, 2001a)), which is one of the most commonly adopted roadmapping processes (de Alcantara & Martens, 2019). Accordingly, for this process, roadmapping workshops were intended as a structured way to capture contributions from key staff and to build consensus.

Fusion start-ups typically have a limited and heavily technically-focused workforce. For the application to Tokamak Energy, it was, therefore, more appropriate to adopt an approach similar to that outlined in (European Industrial Research Management Association (EIRMA), 1997; International Energy Agency, 2014) whereby the roadmap is developed primarily between workshops, rather than through workshops. Whilst new content generation in workshops is encouraged, workshops at Tokamak Energy were instead for formal review of existing content, to scrutinise aspects of the mission, and – where necessary – to make changes (or recommendations for changes) to the roadmap structure\(^{101}\). Most importantly, workshops were intended to gain company-wide consensus on the desired future path.

4.4.2 comprehensively outlines the workshop process as developed for Tokamak Energy. 4.4.3 subsequently outlines additional “focus workshops”, which, as is detailed, were used to develop content on specific issues; as the workshop process was focused primarily on review of content rather than generation. The diagram in Figure 4-9, which shows the roadmapping process (including workshops), has been reproduced on the following page – and relabelled Figure 4-14 – for the convenience of the reader.

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\(^{100}\) With support from the industrial supervisor Dr Alan Costley.

\(^{101}\) A recommendation for a structural change could be the recommendation to add a new sub-layer in the resources and capabilities layer to consider e.g. supply of deuterium (see 6.2).
Figure 4-14 The roadmap development process, derived from application to Tokamak Energy (replication of Figure 4-9).
4.4.2. Review workshops

The features of the workshops held at Tokamak Energy are introduced in 4.4.2.1. The steps in the workshop process: planning and preparation, selection of participants, and activities, are described in the context of Tokamak Energy in 4.4.2.2 through 4.4.2.4. Post-workshop actions, based on the outputs from the process at Tokamak Energy, are detailed in 4.4.2.5.

4.4.2.1. Outline of review workshops at Tokamak Energy

At Tokamak Energy, two review workshops were run at roughly six-month intervals. As noted, review workshops were intended to provide time to review, discuss changes, e.g. newly identified challenges or opportunities, and to update with any progress or setbacks. Specifically:

- The first workshop was used to review the first-pass roadmap; to validate the structure and content. The first workshop was a particularly important activity workshop participants were not present in the majority of the first-pass roadmap development, and thus there was an added need to gain consensus. Workshop participants worked together to generate ideas, particularly regarding developing the scope of future R&D projects and the high-level performance requirements of future machines.
- The second workshop, run approximately six months after the first, focused on reviewing high-level R&D needs, as well as the methods of resolution for the four high-leverage TGIs (4.3.1). Tools and techniques not introduced in the first workshop were introduced to support review. Tools such as linkage grids (4.3.2.2) facilitated the development of new content, particularly on the high-leverage TGIs. The second workshop, unlike the first, was intended to act as a template that could be replicated in subsequent workshops for continuous roadmap review (see 4.7).
- As part of the strategy to embed the roadmapping process in the Tokamak Energy, the process – including control of workshop organisation – was transitioned from the researcher to a member of senior management inside the company following the second workshop. No third workshop was carried out for this research, which is discussed in 5.6.1.1.

4.4.2.2. Planning and preparation

The creation of supporting material for workshop participants, including logistics, an outline of the scope and purpose of the workshop, and important technical information must be created ahead of the workshop. The list below details material prepared for workshops at Tokamak Energy, all of which was disseminated ahead of the workshop:
A workshop agenda outlines the activities for the workshop. The agenda for workshop 2 at Tokamak Energy is shown as an example in Appendix A-2.

A briefing note outlining the purpose(s) of the workshop as well as an overview of roadmapping as a method, including links to additional reading material. The briefing note for Tokamak Energy was based on (Phaal, Farrukh & Probert, 2001a).

Specific workshop objectives – in the form of a set of questions relating to specific areas in which the roadmap must be developed – must also be outlined ahead of a workshop. Table 4-5 provides a list of questions to be used as a template to determine specific workshop objectives, with reference to the layer of the roadmap they relate to. For Tokamak Energy, the questions were based on the list shown in Table 4-5 but customised to focus on specific machines, TGIs etc. A copy is not included for reasons of commercial confidentiality.

A technical information pack, containing the 15 separate TGI files, detailing technical information on each ahead of the workshop. The pack also provided space for participants to make notes of ideas ahead of and during the workshop, which could contribute to the roadmap102. An example of a TGI file is provided in Appendix A-1.

Linkage grids and TRL assessments. A copy of the most recent versions of important linkage grids and TRL assessments were provided103. For the first workshop at Tokamak Energy, only the linkage grid showing TGI interdependencies was available, as the other linkage grids had not yet been developed. Ahead of the second workshop, completed linkage grids were provided (see Figure 4-12). A copy of the Tokamak Energy linkage grids and TRL assessments are not provided in the appendix for reasons of commercial confidentiality.

Articles (e.g. journal publications), reports and plans detailing new or important information relating to the content shown in the roadmap, which provided participants with new or important information on external developments, e.g. on TGI progress in the public programme.

Importantly, the most up to date version of the roadmap must also be prepared. Ahead of the first review workshop, the first-pass Tokamak Energy roadmap was populated with content, per Figure 4-8. Similarly, ahead of the second review workshop, the roadmap was updated to include the ideas and changes from the first workshop as well as new content developed between workshops (as described in 4.3), and ideas from focus workshops (which is described in 4.4.3).

102 In the workshop itself, sticky notes were used to capture information, as described in 4.4.2.4.

103 Copies of the linkage grids and TRL assessments were also printed on A1-sized paper and posted on the walls of the workshop venue.
<table>
<thead>
<tr>
<th>Roadmap layer</th>
<th>Questions</th>
</tr>
</thead>
</table>
| Strategic milestones| - Are the milestones accurate, necessary and achievable?  
- Are there new factors or criteria that impact the existing milestones?  
- Are there any new milestones that should be considered?                                                                                                                                                                                                                                         |
| Machines and R&D projects | - Is the information relating to the proposed machine pathways up to date?  
- Is the information relating to the proposed R&D pathways up to date?  
- Are there any breakthroughs or setbacks (including from experimental results) that affect the pathways? (consider using linkage grid)  
- Are the timescales realistic?                                                                                                                                                                                                                                                                 |
| TGIs                | - Is the information for each TGI (and sub-TGI) up to date?  
- Are there any new TGIs or sub-TGIs that need to be characterised?  
- Are there any technology breakthroughs or setbacks in technology development (internal or external) that need to be captured?  
- What are the methods of resolution for the technologies for each TGI? i.e. how will TGIs be developed: internal R&D, external R&D, collaboration, or watching brief?  
- Are there any new collaborators that could support the development of a TGI?  
- Are the linkage grids connecting TGIs to other roadmap layers up to date?  
- Are the TRLs for the current and desired future state of each TGI (and sub-TGI) accurate?  
- Are proposed TGI R&D plans aligned with the required TRL progression?                                                                                                                                                                                   |
| Resources and capabilities | - Is the information for expected resource needs up to date?  
- Are the linkage grids to resource-load the roadmap accurate? i.e. have the resources to progress the TGIs been considered?  
- Does the company have the capabilities to deliver the plan? If not, where do capabilities need to be improved, and how?                                                                                                                                                                                                                                                                 |

Table 4-5  Questions to guide roadmap development in the review workshop.

4.4.2.3. Selecting participants for the workshop

Much like the roadmap itself, participants involved in a roadmapping workshop must reflect both technology-push and commercial-pull perspectives. All participants involved in a workshop can directly influence others, sharing ideas or concerns with the wider team (Kappel, 2001; Albright & Kappel, 2003). Furthermore, the need to complement scientific minds with entrepreneurial and business minds is important for effective technology innovation, particularly in hi-tech start-ups trying to commercialise technology (Park, 2005; Tura, Hannola & Pynnönen, 2017). For example, a participant from the financial function of an organisation will view a roadmap very differently to a participant with technical knowledge on a particular TGI. Each may have a different understanding of opportunities or risks but may have an entirely different view of which are most critical. They are also likely to have a very different view of what the desired future looks like, which is later
discussed in 5.5.1. If participants are drawn from a range of areas within an organisation, it can facilitate the development of a roadmap that represents a consensus view\textsuperscript{104}. To account for such effects, the selection of participants at Tokamak Energy took careful consideration. Participants were selected based on the perspectives they would provide.

The total number of participants involved in the workshop was limited in order to facilitate the management of the workshop and to ensure that it was a cohesive group activity. Involving large numbers of participants is commonly cited as a limitation in workshop-based processes (Mingers & Rosenhead, 2004). It was decided that nine individuals would be selected for the workshops at Tokamak Energy: three executives, i.e. persons with authority to make high-level strategic and business decisions; three technical managers, i.e. persons with technical authority; and three subject matter experts, i.e. scientists and engineers with specialist knowledge. The specific roles of the participants who were involved in the workshop at Tokamak Energy are shown in Figure 4-15.

Despite efforts to involve a cross-section of participants, as a technology-focused start-up, Tokamak Energy’s staff is predominantly made up of scientists and engineers, and few commercially-focused individuals were available to complement the wealth of technically-focused individuals. Whilst technical expertise is critical, in particular from expert technical consultants who have substantial knowledge to disclose, commercially-minded individuals are also necessary for a balanced assessment. With the exception of specialist consultants under non-disclosure agreements, participants from outside of Tokamak Energy were not considered for involvement in workshops, as the roadmap contains information about the company’s strategy and is regarded as a commercially sensitive document.

Finally, workshops require facilitation by a small management team. In the context of the application, i.e. fusion, facilitators should be technically literate with an understanding of application (i.e. not an external roadmapping consultant), but also an understanding of the

\begin{center}
\begin{tabular}{|l|l|l|}
\hline
\textbf{Executives} & \textbf{Technical management} & \textbf{Technical experts} \\
\hline
- Chief Executive Officer & - Chief Technical Officer & - Senior fusion physicist \\
- Executive Vice Chairman & - R&D director & - Fusion physicist \\
- Commercial Manager & - Engineering project manager & - Fusion engineering consultant \\
\hline
\end{tabular}
\end{center}

\textbf{Figure 4-15} \hspace{0.5cm} \textit{Roles of roadmapping workshop participants at Tokamak Energy}

\textsuperscript{104} Also see (Bouhali \textit{et al.}, 2015).
The PhD researcher and the industrial advisor Dr Costley fulfilled the role of facilitators.

4.4.2.4. Workshop activities

Both the first and second workshops at Tokamak Energy were half-day workshops. The company made the decision that removing key individuals for more than half a day would cause too much disruption due to the small size of the company. However, two participants – one executive and one technical expert – as well as the facilitators, continued into the second half of the day to consolidate the findings of the workshop and to begin updating the roadmap.

Both workshops followed the same basic structure, per the agenda in Appendix A-2, from which the following steps can be distilled:

1. **Introduction:** A member of the senior management team provides opening remarks on their objectives for the workshop\textsuperscript{106}. The roadmapping facilitator(s) give(s) a presentation on the aims and specific objectives of the workshop (per the questions in Table 4-5), as well as a run-through of the agenda. Participants are divided into groups ahead of workshop activities.

2. **Individual group activity:** The three groups of participants are directed to carry out a range of activities relating to the development of the roadmap, one layer of the roadmap or one issue at a time, per objectives specific to the workshops such as those outlined in Table 4-5, and as described in step 1. Ideas, issues or comments generated are captured using sticky notes and placed on the roadmap as appropriate.

3. **Plenary activity:** All groups discuss their ideas with other groups in an orderly manner, moderated by the facilitator. A way forward is determined and required changes to the roadmap, as well as other actions, are documented.

4. **Iteration:** Repeat step 2 and 3 as many times as appropriate until objectives have been reviewed.

\textsuperscript{105} This observation was made during this research and was referred to colloquially by the researcher as “roadmapping from within”. This primarily relates to the role of the researcher as an action researcher, as detailed in 3.5.1.2, and later discussed in 5.1. A similar observation is made by (Amer & Daim, 2010).

\textsuperscript{106} This is similar to the process described in (International Energy Agency, 2014).

\textsuperscript{107} This activity was carried out slightly differently for the second workshop following observations in the first workshop, which is detailed subsequently.
5. **Summary plenary:** Conduct a final plenary activity to identify the most important outcomes of the workshop.

6. **Consolidation:** Majority of participants depart. Remaining participants consolidate key outcomes and actions from the workshop. Importantly, draft changes are made to the roadmap, typically by collating sticky notes from group exercises in step 2.

Steps 2 and 3 form the most important parts of the workshop. However, whilst step 1 is self-explanatory, steps 2 to 5 must be described in further depth using the experience of Tokamak Energy to aid description.

As noted in step 2, the group activity focused on reviewing one layer of the roadmap at a time. However, dedicated time was given for focusing on specific pre-ordained issues, particularly those relating to specific TGIs (typically, high-leverage TGIs). A review of the whole TGI layer can be followed by a review of specific high-leverage TGIs. For both workshops for Tokamak Energy, this activity was carried out in parallel by the three separate groups. The groups were intentionally organised to facilitate discussion and ensure every participant could provide input and to attempt to reduce “groupthink” that may manifest in group discussions, particularly in situations in which there is deference to seniority. For the first workshop, participants were asked to group themselves. This resulted in a perhaps natural separation of technically- and commercially-focused individuals. Not only was there then an imbalance and potential bias towards technology-push or commercial-pull perspectives in each group but in the technically-focused group, it was observed that there was an overt emphasis on in-depth discussions relating to very specific technical issues. Such discussions were deemed to waste time in the context of the roadmap review workshop. Based on this observation, the approach for the second workshop split participants into cross-functional groups, i.e. one from each category outlined in Figure 4-15. Furthermore, the notion that detailed technical discussions are important was an observation from the first workshop that informed the incorporation of focus workshops into the roadmapping method for Tokamak Energy (see 4.4.3). Figure 4-16 shows photographs of the group discussions at Tokamak Energy (photographs are from both workshops).

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108 Groupthink is a common phenomenon in which individuals engaged in group discussion can be unknowingly influenced by others’ views, typically by those with greater seniority or experience, which results in the individual potentially withholding disruptive ideas (Dybå, Dingsøyr & Moe, 2014; Harrell & Bradley, 2009).
Following group discussion (step 2), groups were brought together in a plenary exercise to share information and present key points from their discussions (step 3). Plenary discussions were intended to collate views to move toward a consensus on the issue in focus. This allowed a way forward to be determined and agreed. Key points from the plenary activity were recorded by the workshop facilitators to support the subsequent activity of collating the three separate roadmaps and accompanying post-it notes from each of the groups (step 6). Much like in the Delphi process (see 0), any significant divergence in views was also recorded, and the issue flagged as “requiring further discussion or development”. Following plenary discussions, groups were then directed to move onto the next layer or issue, and the process repeated until all issues had been addressed (step 4).

The first workshop concluded with a short summary given by the CEO (step 5). However, based on the observation of the first workshop, for the second workshop, it was deemed that a summary activity involving the whole team would be more beneficial. A final plenary activity was thus held with the purpose of summarising the findings of the workshop. Each participant was asked to independently note three key issues or ideas from the workshop that they deemed most important. Individual ideas – captured by sticky notes, as is commonly the convention in roadmapping, see (Phaal, Farrukh & Probert, 2007) – were collated and ranked based on prevalence, and subsequently organised through brief whole-
team discussion. The issues or ideas with the largest number of “votes” were then used to understand priorities, and a list of high-level actions was generated.

Following the departure of participants (step 6), the workshop facilitators, accompanied by two individuals from the workshop who held strategic roles in the company reviewed the workshop and its outputs. In particular, the sticky notes from the three separate groups were discussed and collated onto one “master” roadmap. The roadmap was reviewed alongside ideas from the end of workshop plenary (step 5), and a report detailing key actions was produced.

**4.4.2.5. Post-workshop actions**

After a workshop is an optimal time to make any major changes to a roadmap since it is likely that a number of changes are necessary based on the workshop review. Through the use of practical roadmapping software, the whole roadmap must be updated to incorporate structural changes, new content, and any visual formatting. A redacted version of the latest Tokamak Energy roadmap, produced following the second workshop, is provided with a detailed description subsequently in 4.5.

As detailed in step 6 in the previous section, following the workshop, a report summarising the workshop and outlining key actions can also be produced. Such a report outlines the main findings from the workshop activity, including details of any high-level strategic changes and actions for specific staff or teams within the company. For Tokamak Energy, the post-workshop actions report was produced promptly following the conclusion of the workshop and was disseminated to workshop participants. The post-workshop actions report did not only provided an executive summary of the workshop. It also outlined actions that need to be carried out in the near-term by specific members of the team, in accordance with the now updated and consensus-based roadmap. It is important to emphasise at this point that a roadmap cannot “do”. The roadmap for Tokamak Energy, nor the roadmapping team, can deliver what is shown in it. The implementation must come from the team, and then progress, setbacks etc. fed back into the roadmap. Action plans, derived from the roadmap and review workshops, are critical for the implementation of what is shown in the roadmap and are a key step of the process.

Finally, following updates from the workshop, it can also be useful to communicate a roadmap to those in the company not involved in its development, i.e. the staff. However, whilst the format of the roadmap as developed is useful for analysis in the workshop, it is not suited to communication, even with internal staff. The roadmap can be developed for the purpose of enhancing communication with a variety of audiences, including internal ones, which is detailed in 4.6.
4.4.3. **Focus workshops**

Workshops are for reviewing and developing the roadmap rather than for detailed technical discussions. Such discussions are nevertheless important and must be captured as input for the roadmap. Kappel suggests that “mini” workshops are useful for obtaining ideas without the noise associated with the workshop environment (Kappel, 2001). As such, what is here defined as “focus workshops” represented a useful adaptation of the typical roadmapping workshop approach to suit the fusion start-up context. Focus workshops can provide an alternative means to generate specific technical content, whereby individuals – typically, subject matter experts – contribute information on specific areas detailed in the roadmap. Focus workshops are therefore important for generating content and can be regarded as a technique, or perhaps a tool, akin to those outlined in 4.3.

For Tokamak Energy, there was a particular need to develop TGI information. Focus workshops were used as a primary means of capturing specific technical knowledge from subject matter experts on a TGI or sub-TGI\(^{109}\); typically, experts not otherwise involved in the roadmapping process. Focus workshops were held as semi-structured discussions, per (Harrell & Bradley, 2009)\(^{110}\), between the roadmapping team and a subject matter expert, or experts; the researcher set the maximum number to two, in order to avoid turning the focus workshop into a group discussion. The information, and any ideas or new gaps introduced, was captured in the TGI file relating to the discussion. Subsequently, this information was translated into the roadmap either directly or through the support of a linkage grid, since new information typically has an impact on, e.g. other TGIs or machines. Content or structural changes made to the roadmap as a result of focus workshops were recorded, which allowed the roadmap to subsequently be validated at the next whole team workshop.

4.5. **The Tokamak Energy Technology Roadmap**

4.5.1. **Structure and features**

The roadmapping process described throughout this chapter results in a roadmap which is shown in Figure 4-17. An *annotated* version of the same roadmap is provided in Figure 4-18. The roadmap shown in both figures is a representation of the Tokamak Energy

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\(^{109}\) Focus workshops were also used to obtain commercial or business perspectives relevant to the roadmap from executive and technical management.

\(^{110}\) Incidentally, the semi-structured focus workshop process used here was developed by the RAND corporation who also developed the Delphi method.
The roadmap is presented to show the structure, features and format; not to show technical content, and shall be detailed as such.

The roadmap graphic was created using Microsoft Visio\textsuperscript{112}. The time horizon on the roadmap shows the short-, medium- and long-term\textsuperscript{113}, with the scale condensing as it goes further into the future, which is illustrative of the uncertainty and thus fewer activities that can be plotted in the longer-term. Naturally, in the near-term, there is a greater level of depth of information as activities and needs for the near-term are better understood. The roadmap follows a layered, “swim lane”, architecture in which the elements are plotted left to right going forward in time. Strategic milestones are shown by the top layer of the roadmap, with defined milestones indicated by stars. The machines and projects layer highlights the expected steps required to deliver the experimental programme. The TGI layer forms the central and largest part of the roadmap, which indicates the importance of technology development for the fusion context. Some TGI swim lanes, especially high-leverage TGIs, also show sub-TGIs swim lanes providing a greater level of detail. Other TGIs, typically those relevant to the longer-term, are less developed. Finally, the bottommost layer shows the resources required to deliver the overall programme and the capabilities of the company.

The roadmap incorporates colours and shapes as a key design feature, adopting a format similar to that developed in (Albright & Kappel, 2003) in which shapes denote “funding status” and “make or buy” optionality. The roadmap shows linkages between the layers using specific colours, e.g. sub-TGI 1.1 shows that there is a scenario modelling activity to be carried out as a separate R&D project, but to support Machine A. Similarly, the shape of the box illustrates the method of resolution for individual TGI (or sub-TGI) activities. The shapes allow details of current or potential collaborators, as well as who or where the watching brief relates to, to be shown, e.g. see activities on the swim lanes for sub-TGI 4.1 and 4.2. The symbols shown in the resources and capabilities layer provide a visual aid to help understand high-level resource requirements. As noted previously, detailed technical content exists beneath the representation the roadmap shown. Other information is embedded within linkage grids, TGI files, and TRL assessments. The way in which this information can be shown in the roadmap by using functional software is discussed in 5.6.2.

\textsuperscript{111} The roadmap shown in Figure 4-17 (and Figure 4-18) are representations of the roadmap for Tokamak Energy as developed after the second workshop.

\textsuperscript{112} Microsoft® Visio® 2016, version 16.0.12430.20112 32-bit, on Windows 10 OS.

\textsuperscript{113} The Tokamak Energy roadmap shows dates in line with those outlined in 4.1.1.
Figure 4.17  Features and content of the Technology Roadmap developed for Tokamak Energy (redacted). The diagram is based on the Tokamak Energy roadmap, but all technical details have been redacted for commercial confidentiality.
Figure 4-18 An annotated version of the Technology Roadmap developed for Tokamak Energy (redacted). Annotations provided in grey boxes.
4.6. Applications of the Tokamak Energy Technology Roadmap

As detailed in 3.3.3, roadmaps can be developed to support communication. The Tokamak Energy roadmap inherently supported communication in workshops, as detailed in 4.4.2 and discussed in 5.5.1. Beyond its use for internal discussion, however, the content and structure of the internal roadmap can be used to create visualisations to support communication with different audiences and for specific purposes. 4.6.1 describes how the roadmap was developed to support the understanding of uncertainty and risk, and 4.6.2 describes how the roadmap was developed to support communication of the planned development programme to external audiences.

4.6.1. Roadmapping for risk and uncertainty

Uncertainty and risk are inevitable and unavoidable in cutting-edge, high-technology, development programmes (Ilevbare, Probert & Phaal, 2014; Phaal, Farrukh & Probert, 2010). For fusion start-ups, uncertainties arise in several areas, for example, plasma behaviour as higher performance operating regimes are achieved; in material properties as materials are pushed to operate in new environments beyond their currently understood limits; in supply and performance of key materials required for device construction such as tritium or HTS magnet tape. Other uncertainties and constraints, for example, in the workforce, funding and time required to complete a given project, must also be understood. Related to uncertainty, risk is defined as the product of the probability that an (undesirable) event will occur and the subsequent impact of that event. Low risk is thus something that is either unlikely or of little consequence. In comparison, high risk is something that is either likely or of serious consequence. Risks should be identified based upon such criteria, and – where possible – avoided or mitigated. In the context of fusion, the risk presented by, for example, the failure of a heating and current drive system may be high but of low consequence, i.e. a programmatic risk. However, the failure of a tritium handling system, for instance, a tritium leakage may be unlikely but may pose a serious consequence to human health, i.e. it is a safety risk. Whilst safety risks are important, in the context of roadmapping greater focus is on programmatic risk, i.e. what is the risk that a specific path or decision will result in a setback or failure. Whilst roadmapping implicitly provides an understanding of uncertainty and risk – by identifying and exploring future uncertainties and characterising the risk that those uncertainties pose – due to the range of unknowns in the development of fusion, it is instructive to consider uncertainty and risk more explicitly.
Scenario Planning has several beneficial characteristics that make it suitable for application to support fusion start-ups (see 3.1.3.2)\textsuperscript{114}. For Tokamak Energy, using the content and structure developed in the roadmap, Scenario Planning was employed to assess the level of risk associated with future candidate paths and to support decision-making in the face of uncertainty\textsuperscript{115}.

For Tokamak Energy, two possible paths towards the intended goal were determined: the demonstration of net energy gain in a commercially scalable fusion device. On one path; path “A”, an intermediate device is built and technologies tested, and uncertainties de-risked through this device, while the second path; path B, goes directly from the early-stage device but has an additional emphasis on R&D for key technologies in which the results of the R&D are integrated into a later machine. A scenario planning exercise was carried out based on the notion that if multiple scenarios for a path forward are outlined, then one can be chosen on the basis of acceptable risk, i.e. an understanding that avoiding risk altogether is not possible, but in a situation in which one path must be taken, the risks associated with that path are understood and thus deemed acceptable. Moreover, the acceptable risk is not necessarily the level of risk with which one is satisfied. Simply, by understanding the range of possible futures, the risks of pursuing that path are understood and accepted versus the alternatives (see (Derby & Keeney, 1981)).

The scenario planning exercise culminated in the development of the diagram Figure 4-19. All the information was available from the roadmap, or – more accurately – from the two versions of the roadmap that were created to account for the two paths forward (A and B). The information necessary to develop the scenarios were the machine pathways, dates of expected demonstration, technologies to be developed (TGI), and an estimation key resource requirement (manpower and cost). A traffic light system was used as a metric, with green, amber and red used to provide a simplified version of TRLs to illustrate progression through TGI over time. Specifically, path “A” enables the testing of key components and materials potentially in a more relevant environment and builds experience and knowledge, and thus the technology is at a higher TRL. However, development takes longer and at a greater cost. Path “B” may be faster and come at a lower overall cost, but

\textsuperscript{114} Refer to the following publications, which discuss how scenario planning can be used in conjunction with roadmapping (Phaal, Farrukh & Probert, 2010; Ilevbare, Probert & Phaal, 2014; Phaal, Farrukh & Probert, 2009; Hussain, Tapinos & Knight, 2017).

\textsuperscript{115} The notion to develop a risk roadmap for Tokamak Energy was inspired by the use of roadmap to assess risk and uncertainty detailed in (Albright & Kappel, 2003) and by comprehensive research in (Ilevbare, Probert & Phaal, 2014).
it carries a higher risk of failure due to the lower TRL of the technologies. Risk and uncertainty are further discussed in 5.5.3.

Figure 4-19 Relative risk roadmap, produced using the information in the technical roadmap. Shows two possible paths forward, A and B, in the development of a fusion device capable of net energy gain. The key technical uncertainties, an assessment of the cost and time of the pathways can be compared relative to one another. The Tokamak Energy version of the diagram cannot be shown for reasons of commercial confidentiality.

Note: resources scale is arbitrary and for illustration only.
4.6.2. Roadmapping to support external communication

Roadmaps can also be developed to communicate with external stakeholders, for example, potential investors, scientific journalists and researchers in related fields. A very different view of the roadmap shown in Figure 4-17 is required for such audiences. A roadmap for public communication was developed.

A communications roadmap must allow its audience to quickly grasp an understanding of a company’s vision, and the mission – i.e. the steps – to get there. In summary, it must show the core features of the internal roadmap, i.e. the key components that provide a narrative for the company, but in a digestible and eye-catching format116 (see (Phaal, Farrukh & Probert, 2009)). If successfully executed, such a roadmap could be used to elicit deeper discussion around specific aspects of the mission and can be used as a powerful marketing tool. Therefore, with the support of strategic management and the involvement of a lead communications consultant at Tokamak Energy, a meeting was conducted with the goal of developing the communications roadmap. The content in the internal Tokamak Energy roadmap was reviewed, and, after agreeing on content, a design was developed with reference to existing communications roadmaps. Inspiration for the design came from a range of roadmaps, including those in (Kerr & Phaal, 2017; Phaal, Farrukh & Probert, 2010), but specifically those shown in Figure 3-11, Figure 4-21 and Figure 4-22. The communications roadmap for Tokamak Energy was developed from an initial hand sketch created jointly by the PhD researcher and by Dr Melanie Windridge117, and subsequently digitally rendered by a graphic design firm. The resulting published Tokamak Energy communications roadmap is shown in Figure 4-20118.

116 Alternative roadmaps could also be developed to similar effect. Communications roadmaps are discussed in 5.5.2.

117 Dr Windridge is a communications consultant for Tokamak Energy.

118 The Tokamak Energy communications roadmap has had significant impact in its use as a marketing tool. It is used on the company website; in key company presentations to external audiences (e.g. investors and at science fairs) and has featured in media coverage.
Tokamak Energy’s public communications “Roadmap for Faster Fusion”, developed to support public communication. For a view of the current plan and timescales see (Tokamak Energy, n.d.).
As noted, a key step in the development of a communications roadmap is to distil the complex level of information that exists in the comprehensive internal roadmap (i.e. the version shown in Figure 4-17). An effective communications roadmap must reflect the robust and structured internal plan but do so whilst stripping detail back to show only the
core components\textsuperscript{119}. The Tokamak Energy communications roadmap shows expected progression through machines and the intended timescales for their development\textsuperscript{120}. ST-40\textsuperscript{121}, ST-F1 and ST-E1 are aligned with the phases of innovation shown in the S-T-A-M model in Chapter 2, where “pre-cursor”, “embryonic” and “nurture” stages in the S-T-A-M model are translated for Tokamak Energy’s mission as “research and development”, “engineering demonstration” and “commercial roll-out” respectively. This is also analogous to the stages shown in the NASA roadmap in Figure 4-22. There is also an explicit reference to the HTS magnet development programme (TGI #5) as a critical enabling technology, as well as to overall development of TGIs, and to the need for collaboration in the development programme.

The roadmap is also symbolic in design. “Spin-in” technology streams are included to highlight Tokamak Energy’s approach to monitor and adopt relevant external technology developments, e.g. “3D printing”. Similarly, “spin-out” streams for technologies being developed in-house highlight other potential non-fusion commercial opportunities for the company. Both spin-in and spin-out streams include additional unnamed streams which illustrate that new as-yet-unknown technologies or commercial opportunities may emerge. Together, these contribute to the overall aesthetic of the convergent-divergent structure, which was inspired by Chesbrough’s open innovation funnel, as shown in Figure 4-23 and described in 2.5.6.1 (Chesbrough, 2003). The left-hand side of the roadmap shows a converging funnel to illustrate the range of technologies that must be captured and integrated. The centre of the roadmap is focused on ST-F1 as the point at which fusion power gain will be demonstrated. The right-hand side of the roadmap then diverges representing potential commercial routes that have been identified outside of the primary goal of electricity generation, which is positioned centrally.

\textsuperscript{119} This highlights a key distinction between this representation of the Tokamak Energy roadmap and the European Fusion Roadmap. The European Fusion roadmap shown in Figure 3-12 is thematically similar to the Tokamak Energy communications roadmap. However, it is unknown whether there is a more detailed internal version behind it, as with the roadmap developed for Tokamak Energy.

\textsuperscript{120} The timescales shown on the communications roadmap are often a point of contention, which is acknowledged in 8.6.1.

\textsuperscript{121} “ST-40X” is the extended operation of ST-40, which is a key test machine on the path to ST-F1.
Potential non-electricity market applications for fusion were identified as part of the communications roadmap development process by reviewing ideas from (McCarthy et al., 2002b; Kulcinski & Santarius, 1998; Nuttall, Glowacki & Clarke, 2005; Hooper, 2018; Kaslow et al., 1994). The development of the communications roadmap thus provided an initial assessment of information potentially relevant to a "markets" layer (see 5.4.1.2).

4.7. Continuous iteration

Naturally, a multi-faceted R&D programme is dynamic, and there will be developments in both the in-house activities and relevant external fields that will influence the details of the programme. The roadmap in the form shown in Figure 4-17 represents the desired or expected future at a particular moment in time. A roadmap in this static format is, effectively, useful only at the time of printing. In order to retain value as a functional tool, roadmaps must be updated periodically to capture developments and to reflect progress in the development lines, and/or to account for strategic changes. For Tokamak Energy, changes to both the machine pathways, as well as providing an understanding of specific TGIs due to progress, limitations, or technology breakthroughs, were captured through continuous iteration using the roadmap. The roadmap was developed between workshops, updating all accompanying tools: linkage grids, TRL assessments and TGI analyses etc. to ensure that most recent information was presented. These were then used to realign the roadmap to show the necessary changes in strategy or direction via the roadmap. Further activities,
as detailed in Figure 4-14, provided input into the roadmap and facilitated continuous development, to allow the roadmap to function as an effective tool for the company.

Naturally, the timescale over which the process described in this chapter is repeated will depend on the specific development activity. As shown in Figure 4-14, for Tokamak Energy, this is approximately every six months. However, it is more appropriate to develop the roadmap in line with development cycles, i.e. to align with technology projects so that the roadmap can be used as a tool to guide and inform project planning. If utilised in this way, the roadmap becomes a tool to support and facilitate agile innovation, which is discussed in 5.4.2.

**4.8. Chapter Summary**

This chapter has implemented roadmapping to a fusion start-up case study. The resulting roadmapping process and the method to create it, as well as the roadmap itself and its features – both of which are based on action-based research at Tokamak Energy – have been comprehensively outlined.

This chapter, along with Chapter 3, addresses research question 2A, as it details the implementation of Technology Roadmapping to a fusion start-up. However, the effectiveness of the application of the method must be assessed to address research question 2B. Chapter 5 will provide an evaluation of the design, development and implementation of the roadmapping presented in Chapter 4, with reference to the research objectives in 3.5.3, to answer the research questions. Conclusions are collated in Chapter 8.
Chapter 5. Evaluation of roadmapping in fusion start-ups

This chapter will discuss and evaluate the application of the roadmapping method detailed in Chapter 4, addressing research question 2B. Section 5.1 details the researcher's reflections on action research in practice and bias. A workshop with roadmapping practitioners to review the developed process is detailed in 5.2. The application of the roadmapping method to Tokamak Energy is then reviewed. How the roadmapping process and roadmap supported planning, innovation and communication is evaluated against the objectives outlined in 3.5.3 (sections 5.3 to 5.5). Finally, other outcomes, impacts and observations are discussed in 5.6 and 5.7.

Aspects of, and content presented in, this chapter can be found in part or whole in the following peer-reviewed publication, published in the journal Technology Forecasting and Social Change:

5.1. Reflections on action research in practice and bias

A key limitation of action research, particularly in social science, is that it creates “local” solutions that are useful only to the specific case study (Willis & Edwards, 2014). Whilst roadmapping was applied through action research with the aim of developing a process that supports planning, innovation and communication useful for all fusion start-ups, the research has been inherently focused on providing usefulness in the application to Tokamak Energy as the case study. Action research and case study research can be difficult to generalise, but it is contended that aspects of this research – the developed roadmapping process – can be generalised for other organisations. This is in part due to the nature of the problem – i.e. the development of a technology grounded in natural science, and studied in an engineering system context – and in part due to the flexibility of roadmapping as a method, the outputs from this research can be generalisable beyond the application to Tokamak Energy. In particular, it is contended that the developed roadmapping process, roadmap, and outputs are useful to organisations pursuing mission-led agile innovation of hardware-based technology, fusion start-ups or otherwise. However, in order for analysis and discussion of the outputs of the research to understand the usefulness both specifically for the case study, and to draw out the generalisable aspects that apply more broadly, it is first important to acknowledge and discuss the presence of bias.

Bias in qualitative research, particularly in the context of action research, is well characterised (Yin, 2003; Easterby-Smith, Thorpe & Jackson, 2012; Willis & Edwards, 2014; Robson & McCartan, 2016). Generally, research can be contaminated by three sources of bias: topic, procedural and researcher bias. These sources of bias are overlapping and interlinked. Topic and procedural bias refer to bias in the research subject and research method, respectively, and personal bias is the bias introduced by individuals, including both the researcher and the organisation as the subject of a case study. In this research, the main sources of bias are procedural and personal bias. This section discusses the presence of these biases in this research, beginning with reflections on the practical application of the action research methodology.

5.1.1. Action research in practice

Firstly, a key challenge of the action research as a methodology for this research was that whilst the goals of the roadmapping activity were defined (see 4.2.1), it was difficult to fully determine the endpoint, i.e. the point at which these goals were met. As a method that provides foresight and supports the development of strategy, it does not deliver on a set
goal and then ceases to be useful\textsuperscript{122}. It is instead continuously evolved to retain its usefulness to what is a real-world – “living” – organisation. In this research, an endpoint was defined arbitrarily in time (September 2018). Defining an endpoint in this way was at odds with the roadmapping method as inherently continuous. As such, a “handover” process in which the developed process, roadmap, and tools were transferred from the researcher to the company to continue development. This is detailed in 5.6.1.1.

An obvious criticism of this research is that it is based on a single case study. For a roadmapping method for fusion start-ups to be industrially relevant, the researcher deemed that it must be developed in conjunction with an industrial partner (as detailed in 3.5.1.2). Scientific fact (or truth) is rarely based on a single experiment but usually on multiple experiments replicated with altering conditions, to understand what universal truths exist (Yin, 2003). An alternative approach (to conducting research in a single case study) could have been to involve multiple fusion start-ups to develop a generic but fusion sector-specific roadmapping framework that each company could then adopt and further adapt. However, as the application of roadmapping to fusion – and more broadly in agile innovation in hi-tech hardware development – is limited, a single case study is an appropriate approach. Moreover, this strategy would require industrial cohesion in what is a competitive, resource-constrained, and fast-moving world. Logistically, as well, with many start-ups based in the U.S., such a study would be challenging to conduct in a rigorous manner compared with a single, focused case study. The application of the developed method is developed with the notion that it can, of course, be applied beyond the single application in future to test it.

Relatedly, while Tokamak Energy is considered a “typical” fusion start-up, the company’s mission is unique, and the company has its own organisational culture, management styles and practices. If the research had been conducted in a different fusion start-up, aspects of the process would have developed differently. Despite this, the technical challenges in the Tokamak Energy programme are likely to be similar to those experienced in other fusion start-ups, all of which face very similar engineering systems challenges. The research was collated and presented in Chapter 4 in such a way that technical content was kept separate from process development. Technical content and mission criteria from Tokamak Energy were used to emphasise or illustrate the rationale for the specific methodological decision (or for context, e.g. reference to specific TGIs). Naturally, however, the roadmapping process was developed towards the needs of the company and in response to events and decisions made by the company that was largely out of the control of the researcher. For example, the decision to use the early-stage roadmap to assess the risk associated with

\textsuperscript{122} Despite this, this was often how the method is perceived, which is discussed in relation to the embedding of roadmapping in Tokamak Energy in section 5.6.1.2.
two pathways was driven by a high-level strategic challenge faced by senior management. The potential for the roadmap to provide usefulness to this specific need was recognised, but not preconceived, by the researcher. In other words, whilst the challenge to develop a roadmap for risk fitted with the scope of the research (roadmapping to support communication), the specific tools and techniques to develop the solution were not anticipated by the researcher and were specific to the company. This example, in fact, indicates that the researcher avoided a common form of procedural bias in case study research: that researchers seek problems to fit a method to substantiate its usefulness, rather than the other way around (Yin, 2003).

5.1.2. Procedural bias

Whilst most scientific experiments involve a full understanding of the issues under study prior to conducting the research, and thus – often standardised – methods can be determined ahead of the research, case study action research often requires contextual adaptation. Unlike other scientific methodologies (particularly those heavily grounded in natural and physical science), action research does not tend to follow set procedures (Calhoun, Starbuck & Abrahamson, 2011). In fact, case study research conducted in an organisational setting is often criticised for lacking procedural rigour in this regard (Yin, 2003). This was evident in this research. Technology Roadmapping was selected for its flexibility to be applied to the problem (out of several futures methods which were assessed for their suitability for supporting fusion start-ups, against the 5 C’s, see 3.1.2). Roadmapping is inherently adaptable and does not necessitate a set procedure to be followed. As such, the researcher was not bound to the notion that roadmapping should be deployed in a rigid manner. On the contrary, it was dynamic and responsive. Neither the tools and techniques nor the specific outputs were defined at the beginning of the research. Where necessary, the researcher deviated from preconceived ideas (the use of tools and techniques already known the researcher from training and literature study) to achieve a useful output. For example, it was initially hypothesised that roadmapping workshops would be a key part of the process for content generation (similar to T-Plan (Phaal, Farrukh & Probert, 2001a)). However, realising the limitations with the specific approach for the application, focus workshops, which involved the collection and collation of knowledge from experts, were used in place of longer whole team workshops. The process was adapted to suit the context, with the developed roadmapping process for Tokamak Energy informed and guided by – but not dictated by – established theory and practice. The method was thus deployed in an explorative and responsive manner, evolving – to a large extent – organically.

The method of roadmapping hence avoids the introduction of procedural bias. That all aspects of the developed roadmapping framework are adaptable, e.g. the frequency of
workshops can be increased; different TGIs can be developed; different tools can be used to identify commercial drivers; different layers can be added to the roadmap, suggests that the process has a large degree of generalisability. These adaptations can be carried out whilst following – and without substantially deviating from – the developed process. However, all decisions were made based on the perceived usefulness to Tokamak Energy. This means that one solution that was useful for Tokamak Energy may not be useful for another fusion start-up. This relates primarily to the presence of personal bias.

5.1.3. Personal bias

The results of qualitative research are “not determined simply by the characteristics of the thing observed; the characteristics and perspective of the observer also have an effect” (Robson & McCartan, 2016). Personal bias can be introduced in by the researcher who interprets research methods or data to fit with the researcher’s own ideas. Such bias can thus – entirely organically, i.e. without intention – push the research in a direction to be advantageous to achieving the intended outcomes or personal beliefs of the researcher.

Robson and McCartan suggest that practitioners can make better decisions by engaging in action research (Robson & McCartan, 2016). Specific problems and needs within the company were addressed by the researcher who had a subjective understanding of the problem in the organisational context, but simultaneously an objective understanding of potential solutions. Better recognition of the needs thus allows a more appropriate response in the application of a research method by the researcher. The researcher was able to understand that what would be objectively useful from a methodological standpoint. As such, the roadmapping method, and the goals of the research, evolved over time and in a responsive manner. On the other hand, despite having a better understanding of needs, as well as increased situational awareness (an understanding of cultural and behavioural sensitivities), the researcher is more likely to introduce personal bias when embedded within an organisation. The researcher, like all individuals, has their own worldview and perception of reality. Whilst personal bias presence introduced by the researcher was unavoidable – and certainly impacted the direction of the research – the placement of the researcher inside the organisation also supported the avoidance of “ivory towerism”. This is defined here as situations in which the researcher is viewed as doing something useful only for their own research purposes, instead of research that is valuable to the organisation. This dynamic also allows the research to be democratised, with ideas and input from the company in both the problem, and the solution has wider ownership beyond just the researcher. This facilitates wider dissemination of the research and brings an extra layer of commitment to success from those in the organisation under study. In the context of this research, this may improve the adoption and use of roadmapping as a tool within the company (Robson & McCartan, 2016). Despite this perceived benefit, the way in which the roadmapping was
not suitably embedded within the company suggests that the process was not fully democratised in this way. This is discussed in section 5.6.1.

Personal bias can also be introduced by stakeholders – defined as those who will be impacted during or by the research and its outputs – other than the researcher. In this research, academic supervisors and senior management within the company were the key stakeholders and directed the research explicitly and implicitly in different ways. The role of the action researcher is to identify the most useful directives from such stakeholders, in order to produce outputs that are of both academic usefulness and practical action (for the company), to satisfy both sets of stakeholders and to meet the objectives of the research. Easterby-Smith et al. suggest that this balance is particularly important for successful management research (Easterby-Smith, Thorpe & Jackson, 2012).

Regarding academic supervision, the roadmapping process, tools and techniques were developed through consultation and guidance of the industrial supervisor as well as the researcher’s supervisory team throughout. As such, the researcher was guided by supervisors but remained in control of the overall research direction. Greater bias was introduced by the case study, Tokamak Energy. In action research deployed to support the management of a real-world organisation, certain decisions or actions associated with the deployment of a research method which is deemed useful to a researcher may not be seen as useful by a company (or vice versa). This can lead to divergence in the usefulness of the process developed. It was the decision of the researcher to develop, for example, the public communications roadmap in this research. The company were supportive of the research direction in this instance but did not perceive it. However, there were other instances in which the company did not perceive that the research was heading in a direction of interest. In the earliest stages, the company was involved in defining the goals of the roadmapping activity (see 4.2.1), which explicitly defined the requirements of future research. Later in the process, the decision to run a half-day rather than a full-day workshop was driven by the capabilities of the company (see 4.4.2). The researcher’s idea to include external experts in workshops to provide an alternative and neutral perspective was not aligned with the company’s views (in this case, principally due to concerns over confidentiality). Finally, the importance of including a comprehensive commercial layer – detailed in-depth in section 5.4.1 – was deemed important to the next-step development of the roadmap by the researcher but was perceived to be of lesser importance to the company at this stage123. Unlike in social science (or clinical) research, when conducting

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123 This may highlight why the company perhaps sought a roadmap to support technology and R&D management rather than innovation management (see Figure 2-14), which underpins why many in the company saw roadmapping as an advanced Gantt chart, which is further discussed in 5.6.1.3.
management research inside a real-world organisation, the researcher is often the least powerful party (Easterby-Smith, Thorpe & Jackson, 2012). In such circumstances, the researcher may feel pressured into altering the research direction out of fear of damaging personal relations. It was, therefore, the responsibility of the researcher to abide by ethical research practice in influencing the direction of the research and aligning with the company’s requirements and desires.

Finally, a key ethical issue arose in collating and writing up the research; which is again common in qualitative management research, see (Easterby-Smith, Thorpe & Jackson, 2012). In writing up research results, the researcher had to consider both the perspective of the company – which did not wish to disseminate technical content about its programme – and the perspective the research objective to produce a broadly useful and generalisable roadmapping process for fusion start-ups. The information presented in the thesis was thus based on real-world technical content and the workings of a real-world organisation, but the value and usefulness are extracted with reference to, rather than explicit description of Tokamak Energy’s programme. At the same time, it provided a broader framework that could be more readily applied to other fusion start-ups, or in other contexts. The research presented in this thesis – and in the publication by the researcher (Pearson et al., 2020) – is written as such. This was a conscious decision by the researcher, the company, and academic supervisory team, based on the requirements of all parties as an appropriate and ethical approach.

5.2. Assessing generalisability: Review workshop with industrial practitioners

To assess whether research is carried out objectively – in the context of this research, to understand the extent to which the findings are generalisable to other fusion start-ups – it is informative to consider the usefulness of the research beyond the case study for which it was developed. Four categories to test the validity of qualitative research are outlined in (Kidder & Judd, 1986). The significance of each category depends on the focus of the research:

- Construct – the measurements of values
- Internal – the identification of causal links whilst accounting for noise
- External – understanding the extent to which the research can be generalised
- Reliability – ensuring that the research can be replicated (i.e. process)
Although the reliability of the research, i.e. whether it can be produced again, is important\textsuperscript{124}, the principal measure of the validity of this research relates to the external validity, which is here interpreted as a means to measure generalisability. Whilst biases were considered during all stages of the research – planning, implementation etc. – to be as objective as possible, to infer that the research is generalisable to organisations outside of the Tokamak Energy case study, the research outputs must be objectively assessed.

A review workshop involving industrial roadmapping practitioners, including academics, was organised to provide an assessment and critique of the developed roadmapping process and its outputs, as detailed in Chapter 4. The workshop was designed to question why certain decisions were made in the development of the process, and to assess the extent to which it is generalizable from an impartial third party.

5.2.1. Review workshop

The review workshop was carried out at the University of Cambridge Institute for Manufacturing with a group of industry practitioners from the Strategic Technology and Innovation (STIM) consortium in February 2019. The process for the review workshop, referred to hereafter as the STIM workshop, was based on previous research by Hirose (Hirose, 2017). The STIM workshop was designed to evaluate the application of roadmapping and to elicit feedback, rather than to validate the application. To validate the method would require reproducing the process with other organisations similar to Tokamak Energy, which is beyond the remit of this research.

5.2.1.1. Purpose

The STIM workshop was centred around the review of two diagrams showing the roadmapping process, the technical roadmap (Figure 4-17), and the two visualisations detailed in 4.6.1 – for risk (Figure 4-19) and public communication (Figure 4-20). Following a presentation detailing some of the key details to the application to Tokamak Energy, the diagrams were reviewed by the workshop practitioners with two key purposes:

1. To review and evaluate the application of roadmapping to Tokamak Energy to specifically assess:
   a. The generalisability of the roadmapping process to other similar problems.
   b. How the roadmapping process could be improved.

\textsuperscript{124} The process outlined in Ch. 4 – and published in the journal article by the researcher in (Pearson et al., 2020) – is detailed such that the results of this research can be replicated.
2. To review and critique whether the diagrams were clear and effectively communicated the process (or message, in the case of the roadmap visualisations):
   a. The effectiveness of the diagram to communicate its intended purpose.
   b. How to improve the clarity of the diagrams.

As shall be detailed, feedback from the workshop resulted in limited suggestions to alter the roadmapping process itself, but for several key changes to the diagrams. In fact, some of the diagrams shown previously in Chapter 4 – Figure 4-4, Figure 4-9, Figure 4-17 and Figure 4-19 – were developed and edited based on the feedback from the STIM workshop. These are shown as side-by-side comparisons to illustrate the changes later in Figure 5-8.

5.2.1.2. Participants

Workshop participants had a range of experience in roadmapping, as well as technology and innovation management. Table 5-1 shows participants (names of participants and organisations are redacted for confidentiality).

<table>
<thead>
<tr>
<th>Affiliation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi-tech electronics company</td>
<td>Manager</td>
</tr>
<tr>
<td>Global heavy industries manufacturer</td>
<td>Principal research engineer</td>
</tr>
<tr>
<td>UK Government Authority</td>
<td>Technology assurance manager</td>
</tr>
<tr>
<td>UK Government Authority</td>
<td>Strategic development manager</td>
</tr>
<tr>
<td>IT and telecommunications services</td>
<td>Technology strategist</td>
</tr>
<tr>
<td>Aerospace (defence) company</td>
<td>Portfolio manager</td>
</tr>
<tr>
<td>Global healthcare company</td>
<td>Technology translation</td>
</tr>
<tr>
<td>Hi-tech software company</td>
<td>Chief executive</td>
</tr>
<tr>
<td>UK university-led consultancy group</td>
<td>Senior solution development specialist</td>
</tr>
<tr>
<td>UK university-led consultancy group</td>
<td>Industrial associate</td>
</tr>
<tr>
<td>International university</td>
<td>Post-doctoral researcher</td>
</tr>
<tr>
<td>International university</td>
<td>Masters student</td>
</tr>
</tbody>
</table>

Table 5-1 Participants involved in the review exercise at the STIM workshop (names and affiliation redacted for confidentiality).

5.2.1.3. Workshop overview

Workshop participants were divided into two groups to review the diagrams. Participants were asked to record their feedback using sticky notes; pink notes were for critical feedback and green notes for positive feedback. Figure 5-1 shows both groups reviewing a diagram in the STIM workshop.
Participants were guided by questions shown in Table 5-2. As detailed in 5.1.2.1, questions relating to the roadmapping process were centred on the clarity of the structure and process, process novelty, and generalisability; and questions relating to the roadmap visualisations were centred around their clarity.
<table>
<thead>
<tr>
<th>Topic</th>
<th>Diagram</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-pass roadmap process</td>
<td>Figure 2</td>
<td>• Process: Does the process shown in the diagram make sense?</td>
</tr>
<tr>
<td>(5.2.2.1)</td>
<td></td>
<td>• Structure: Is the layout of the diagram clear, and does it make sense?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Completeness: What, if anything, is missing from the diagram?</td>
</tr>
<tr>
<td>Roadmap development and embedding process</td>
<td>Figure 3</td>
<td>• Novelty: How is this technology roadmapping method unique? How is it</td>
</tr>
<tr>
<td>(5.2.2.2)</td>
<td></td>
<td>different from other existing approaches?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Generalisability: To what extent could this process be applied to other high-tech start-ups?</td>
</tr>
<tr>
<td>Tokamak Energy mock-up Technology Roadmap</td>
<td>Figure 4</td>
<td>• Function: To what extent does each of the visualisations serve its</td>
</tr>
<tr>
<td>(5.2.2.3)</td>
<td></td>
<td>intended purpose?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Clarity: Is the layout of the visualisations clear? Do they make</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sense? Are they self-explanatory?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Completeness: What, if anything, is missing from the diagrams?</td>
</tr>
<tr>
<td>Relative risk roadmap(s) (Pathway A and B)</td>
<td>Figure 5 (A) and Figure 5 (B)</td>
<td>• Evolution: Is it clear that the risk and communications visualisations are derivations of the technical “master” roadmap visualisation?</td>
</tr>
<tr>
<td>(5.2.2.4)</td>
<td></td>
<td>• Generalisability: To what extent could these visualisations act as a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>template for use by other high-tech start-ups?</td>
</tr>
<tr>
<td>Tokamak Energy communications roadmap</td>
<td>Figure 7</td>
<td></td>
</tr>
<tr>
<td>(5.2.2.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 5-2  Questions to guide review in the STIM workshop.**

5.2.2. Feedback from the STIM workshop

The feedback from the STIM workshop is collated in subsections 5.1.3.1 through 5.1.3.5. Feedback from participants has been collated where appropriate and paraphrased for clarity. None of the feedback detailed should be taken as verbatim.
5.2.2.1. **First-pass roadmap process diagram**

Figure 5-2 (overleaf) shows the version of the first-pass roadmap process diagram that was reviewed in the STIM workshop. Comments from the participants and resulting modifications to the process and diagram are shown in Table 5-3.

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Critical feedback</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• The steps can be followed to produce a first-pass roadmap.</td>
<td>• How the timeframe is determined is unclear.</td>
<td>• The timeframe is determined by the scope of the application (as detailed in 4.2.1).</td>
</tr>
<tr>
<td></td>
<td>• Time, sequencing of machines, projects and technology development in the “swim-lane” approach on the roadmap is clear.</td>
<td>• Strategic milestones layer needs to highlight commercial and strategic drivers and should be augmented by a “markets” layer to identify competitors, signals, trends, drivers.</td>
</tr>
<tr>
<td></td>
<td>• The layers of the first-pass roadmap would be applicable beyond only fusion start-ups</td>
<td>• A risk matrix could be incorporated to show the consequence and impact of technologies failing, e.g. which gaps require a “breakthrough”, and which require incremental improvement?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lack of a “markets” noted as a significant limitation; strategic milestones are not enough. Discussed in detail in 5.4.1.2.</td>
</tr>
<tr>
<td><strong>Diagram</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Not clear where to start – what is the order? Numbering would be useful.</td>
<td>• Some arrows are misleading.</td>
<td>• Whole diagram reformatted to show steps as numbered and sequential</td>
</tr>
<tr>
<td>• Shapes and colours make the diagram complex</td>
<td>• The 3-by-3 matrix as a starting point is useful, but it is unclear how it translates into layers of the roadmap.</td>
<td>• Colours, shapes and arrows adjusted accordingly</td>
</tr>
<tr>
<td>• The 3-by-3 matrix as a starting point is useful, but it is unclear how it translates into layers of the roadmap. Furthermore, questions on 3-by-3 matrix need to be clearer</td>
<td>• The sub-layers under “machines and projects” and “resources and capabilities” should be detailed.</td>
<td>• Sub-layers of the first-pass roadmap diagram deemed too complex to be illustrated clearly. To resolve the problem, steps 3 and 4 were enlarged as separate figures to be presented alongside the updated process diagram</td>
</tr>
</tbody>
</table>

**Table 5-3**  *Feedback on the first-pass roadmap process from STIM workshop participants.*
Figure 5-2 STIM workshop version of the first-pass roadmap process diagram.
5.2.2.2. Roadmap development and embedding process diagram

Figure 5-3 (overleaf) shows the version of the roadmap development and embedding process diagram reviewed in the STIM workshop. Comments from the participants and resulting modifications to the process and diagram are shown in Table 5-4.

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Critical feedback</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It is clear that the process follows on from the development of a first-pass roadmap.</td>
<td>Duplication of the comment for the diagram in Figure 5-2 that the strategic milestones layer needs to highlight commercial and strategic drivers. And – again – that it should be augmented by a “markets” layer to identify competitors, signals, trends, drivers.</td>
<td>Again, the lack of a “markets” layer is noted as a significant limitation; strategic milestones are not enough. Discussed in detail in 5.4.1.2</td>
</tr>
<tr>
<td>The process could be applied to other similar complex hardware-based problems that require high capital such as The Human Genome Project, X-prize foundation ventures, and electric flight.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diagram</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td>Lots of information (&quot;cognitively loaded&quot;) and therefore hard to follow.</td>
<td>Diagram restructured to improve clarity.</td>
</tr>
<tr>
<td></td>
<td>Clarity could be improved through “swim-lanes” for different activities, i.e. roadmap development, workshops, inputs, outputs all on individual lanes.</td>
<td>“Swim-lanes” introduced to delineate activities into individual lanes.</td>
</tr>
<tr>
<td></td>
<td>The timeline should be moved to the bottom of the diagram to improve clarity.</td>
<td>Timescale placed at bottom of diagram.</td>
</tr>
<tr>
<td></td>
<td>Inputs and outputs are complicated; in particular, inputs need to be better defined.</td>
<td>Inputs and outputs re-worded and better defined.</td>
</tr>
<tr>
<td></td>
<td>Duplication of arrows on “continuous iteration” (final step) is unnecessary.</td>
<td>Additional arrows on continuous iteration removed.</td>
</tr>
<tr>
<td></td>
<td>Reduced emphasis on workshops in the process should be made clearer</td>
<td>Workshops are shown below the central line of roadmap development, to show supporting role.</td>
</tr>
<tr>
<td></td>
<td>Unclear whether activities are team or individual processes.</td>
<td>Whether activities are team or individual processes too complex to illustrate.</td>
</tr>
</tbody>
</table>

Table 5-4 Feedback on the roadmap development and embedding process from STIM workshop participants.
Figure 5-3  STIM workshop version of the roadmap development and embedding process diagram.
## 5.2.2.3. Tokamak Energy mock-up technical roadmap

Figure 5-4 (overleaf) shows the version of the Tokamak Energy mock-up technical roadmap reviewed in the STIM workshop. Comments from the participants and resulting modifications to the process and diagram are shown in Table 5-5.

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Critical feedback</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive feedback</td>
<td>Layers of the roadmap assumed to have significant content beneath them that can’t be shown. Are there linkages? How is the content managed?</td>
<td>Roadmap activities are linked through linkage grids (see 4.3.3), and the content beneath the roadmap is managed manually. This comment highlighted a need for software, which is discussed in 5.6.2.</td>
</tr>
<tr>
<td>N/A</td>
<td>Although the content in the roadmap is a mock-up, there are many “general” activities, i.e. content not directly connected to a machine or project (denoted by a black border). What does “general” mean? If it is general, is it really necessary? Or does it enable other technologies and therefore is it on the critical path? This should be clarified.</td>
<td>Machines are required to develop or test TGIs, and to meet milestones to demonstrate progress</td>
</tr>
<tr>
<td>“Resources and Capabilities” layer is clearer than in the first-pass process diagram; symbols are useful</td>
<td>Layer for strategic milestones missing. Currently, milestones are integrated into layers, which is messy and unclear.</td>
<td>Connections can be shown on a digital version of the roadmap, but software is needed (see comment above)</td>
</tr>
<tr>
<td></td>
<td>What does “machine” mean? Is it to produce the machine, set up the machine to test technology or both? It should be defined.</td>
<td>Producing a version of the roadmap for internal communication is discussed in 5.5.1.3.</td>
</tr>
</tbody>
</table>

| Feedback on the Tokamak Energy mock-up technical roadmap from STIM workshop participants. |
5.2.2.3.1. On “general” technology development

Comments relating to “general” technology development in the roadmap suggest an important clarification must be made. General technology development (shown by the black borders in the Technology Roadmap) refers to instances where technology already exists or is considered to be at a high TRL than other technologies that require specific development projects or testing on machines. It can be considered as “work to do”, i.e. technology which must be adapted to the Tokamak Energy application or developed from an already high TRL, e.g. TRL 6, rather than technologies that are at comparably low TRLs. Without them, the programme cannot succeed. Naturally, therefore, general technology development must be integrated into projects or machines. However, to delineate from dedicated technology development that is required, they are not shown as connected to projects or machines in the roadmap.
Figure 5-4  STIM workshop version of the technical roadmap developed for Tokamak Energy.
5.2.2.4. Relative risk roadmap(s)

Figure 5-5 and Figure 5-6 (overleaf) show the version of relative risk roadmaps reviewed in the STIM workshop. Comments from the participants and resulting modifications to the process and diagram are shown in Table 5-6. Note that comments on the relative risk roadmaps related only to the diagram, not the process.

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Critical feedback</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cost estimates are useful; if showing to an investor, the first question will always be &quot;how much is it going to cost?&quot; (although investors will want to see a more detailed version, too)</td>
<td>• The benefits of one pathway over the other are not clear. Difference in timescale, cost and risk appear negligible without a direct comparison. Suggest combining into one diagram.</td>
<td>• The separate risk roadmaps were combined to enable comparison of the differences in timescale, cost, and risk.</td>
</tr>
<tr>
<td>• Technology progression clear through TRL traffic light system</td>
<td>• Are there steps beyond the FOAK? What is the TRL of the FOAK? It is unclear.</td>
<td>• A FOAK will be the first commercial reactor. It is therefore expected to demonstrate technologies to TRL 9.</td>
</tr>
<tr>
<td>• Other visualisations could be produced to emphasise similarly important aspects of the programme from the information in the roadmap. Additional visualisations are discussed in 5.5.2.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-6 Feedback on the relative risk roadmap(s) from STIM workshop participants.
Figure 5-5  STIM workshop version of the relative risk roadmap for Pathway A, to be viewed in conjunction with Pathway B (mock-up version with details redacted).
Figure 5-6  STIM workshop version of the relative risk roadmap for Pathway B, to be viewed in conjunction with Pathway A (mock-up version with details redacted).
5.2.2.5. Tokamak Energy communications roadmap

Figure 5-7 (overleaf) shows the version of the Tokamak Energy communications roadmap reviewed in the STIM workshop. Comments from the participants are shown in Table 5-7. Note that comments on the Tokamak Energy communications roadmap related only to the diagram, not the process.

<table>
<thead>
<tr>
<th>Positive feedback</th>
<th>Critical feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Simple and effective graphic design to share the vision and mission. Appropriate level for public understanding and well-crafted for external engagement</td>
<td>• Convergence on 2025 implies that the solution is finalised by this point, yet it shows the FOAK in 2030, so why is convergence not on 2030?</td>
</tr>
<tr>
<td>• Can be a “Segway” into more in-depth conversations as it provokes inquiry about elements of the programme</td>
<td>• Dates need explanation: Are they determined by the technology programme? Are they purely aspirational? Is there any marketing bias from the company?125</td>
</tr>
<tr>
<td>• Clear link between the communications roadmap and the “internal” roadmap in terms of its structure and time-based layout</td>
<td>• Technology gaps are presented but with no explanation. In particular, it is not clear whether all technology gaps are at the same level. Which are the hardest gaps? They look like they will be solved incrementally.</td>
</tr>
<tr>
<td>• The process used to create it could be adopted by others seeking to produce communications roadmaps</td>
<td>• Will the “winner” (of the race to fusion) take all? What about the competition?</td>
</tr>
<tr>
<td>• In addition to public communication, can be used to show company staff how their work is useful to the company’s overall mission</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-7 Feedback on the Tokamak Energy communications roadmap from STIM workshop participants.

The communications roadmap was not directly altered as a result of feedback. Comments were recorded to be implemented by Tokamak Energy in the next updated version.

125 Although the communications roadmap is based on the internal roadmap, timescales on the internal plan may be subject to internal bias. The timescales shown on the roadmap are discussed in 5.6.3 and latterly in 8.6.1.
Figure 5-7  The Tokamak Energy communications roadmap (replication of Figure 4-20).
Modifications to all the roadmapping diagrams are shown, for the purposes of graphical comparison for the reader, in the diagram below (Figure 5-8).

Figure 5-8 Modifications to roadmapping process diagrams and roadmaps following STIM workshop review. Top to bottom: First-pass roadmap process diagram (refer to Figure 4-4 for an enlarged version of the updated diagram); roadmap development and embedding process diagram (refer to Figure 4-9 for an enlarged version of the updated diagram); mock-up of the roadmap (structure) developed for Tokamak Energy (refer to Figure 4-17 for enlarged version of the updated diagram; mock-up relative risk roadmap(s) for Tokamak Energy (refer to Figure 4-19 for an enlarged version of the updated diagram).
5.2.3. Limitations of the STIM workshop

A key observation is that the STIM workshop was not appropriately designed to elicit comments relating to the roadmapping process. Unintentionally, the STIM workshop instead saw participants focusing on assessing the utility of the diagrams. Despite this, several useful ideas and points were raised by participants, specifically on the need for a “markets” layer, the need for additional visualisations, and the need for software. These are discussed later in this chapter.

Furthermore, the diagrams have been improved from STIM workshop feedback. Modifications to the diagrams are shown by the thumbnails collated in Figure 5-8.

5.2.4. Reflections on the generalisability of the roadmapping method, post-STIM workshop

The roadmapping method applied in this research was intended to use Tokamak Energy as a case study, and as a real-world example of a high-tech start-up that adopts an agile innovation approach, but with a focus on hardware, high complexity, long time horizons (and long timescales to an ROI), and significant uncertainty. Some STIM workshop participants commented on the generalisability of the process during the review workshop, stating that the process appeared to be applicable to other similarly high-tech start-ups (see 5.2.2.3). Despite this, as detailed in 5.1, it is not possible to definitively determine whether the roadmapping method – specifically the process – is generalisable to other start-ups in this space (i.e. whether it is useful beyond Tokamak Energy). However, the process must be applied to other organisations in similar sectors to conclude that it is wholly generalisable. Recommendations to validate the generalisability of the developed roadmapping process are provided in 8.5.2.

5.3. Roadmapping to support planning

This section evaluates how the roadmapping method detailed in Chapter 4 supported planning per the research objectives outlined in 3.5.3. Contributions and limitations are also discussed.

5.3.1. Development of TGIs

Both TGI analysis (4.3.2.1) and focus workshops (4.4.2) were created as part of the roadmapping process to develop an understanding of future technology challenges. Both
activities informed traditional project planning for near-term TGIs\(^{126}\) but also provided a means to scope out longer-term TGIs that would otherwise not be in focus due to resource constraints. The roadmapping process explicitly considered all TGIs and helped to determine high-level R&D needs for long-term TGIs. Even for TGIs with high uncertainty, understanding to some degree how they may impact near-term activities can be useful. For example, the high-level requirements for tritium breeding blankets for a commercial fusion power plant can still be defined, e.g. a tritium breeding ratio (TBR) >1 (more tritium produced than burnt by the fusion reaction), a 10-year component lifetime etc. Although these requirements are likely to change, defining broad needs facilitates planning.

5.3.2. Methods of resolution to understand technology gaps

As outlined in 4.3.2.3, the roadmapping process incorporates the means to identify a method of resolution for technology development challenges. Simply, identifying methods of resolution supports planning as it helps to determine whether a technology is developed in-house, or whether it is developed external to the company (through collaboration or as a watching brief), and thus functions as a “make or buy” tool. How including the methods of resolution in the roadmap supports open innovation is detailed in section 5.4.3.

5.3.3. Identification of TGI owners

Part of the process not described in Chapter 4 involved the identification of specific “TGI managers”. TGI managers were staff identified to be responsible for all activities that relate to a specific TGI\(^{127}\). The identification of TGI managers ensured that all areas of future development are actively monitored and considered. TGI managers are tasked with fully understanding their TGI in the roadmap, including how it may affect other aspects of the programme (via linkage grids). For example, the TGI manager for TGI #9 (fusion materials), could be tasked with determining in greater detail the requirements of ST-F1 and ST-E1, and to provide initial component or technology systems lists, materials options, potential collaborators, and estimated resource needs, to allow information to be integrated into the roadmap.

\(^{126}\) For Tokamak Energy “near-term” relates to TGIs that affect the current experimental programme or machine.

\(^{127}\) The identification of TGI managers – in addition to the identification of potential collaborators using the methods of resolution – means that the roadmap addresses the “who” and to some extent the “where” elements of the “6 W’s” (see 3.2.1).
5.3.4. **Linkage grids**

Linkage grids can identify interdependencies and connect disparate elements of a roadmap, both within and across layers. Moreover, linkage grids can provide a “reality check” on the elements on a roadmap, ensuring that elements are consistent in time. For example, if Tokamak Energy has set a strategic milestone for 2021, a linkage grid can be used to identify and estimate the machine performance requirements. In turn, technologies that must be developed, and the time and resource to develop them, can determine whether the strategic milestones will be met\(^{128}\). Therefore, the time taken to develop technology can provide a hard constraint on meeting the strategic milestone, but equally the time-based target provided by the milestone can drive technology to be developed in the shortest possible time. Linkage grids thus support the development of a plan that is both ambitious yet realistic. Of course, plans must be altered over time to account for unforeseen events, new drivers, breakthroughs or setbacks. Linkage grids can be updated alongside the roadmap to identify and explore emergent issues and changes.

5.3.4.1. **Limitations of linkage grids**

Unlike roadmaps, linkage grids are not explicit in the time domain and therefore must be transposed onto a roadmap to identify the time aspect of linkages. Transposing linkage grids onto a roadmap is a complex task. At Tokamak Energy, it was done manually. The link between ST-E1 and Remote Handling (TGI #10) provides a good example of the complexity of the internal and cross-layer linkages. ST-E1 requires remote handling to safely and efficiently remove and replace damaged components from inside the reactor. Remote handling systems thus relate to several other TGIs, principally the tritium breeding blanket (TGI #12 – which must be periodically replaced), the first wall (TGI #9) and the diagnostics (TGI #4)\(^{129}\). Similarly, conditions such as permissible downtime for maintenance represents a commercial driver, which can be accounted for if further linkage grids are developed to consider commercial drivers. Finally, resources and capabilities required to develop remote handling can also be identified in linkage grids, for instance, hiring staff and buying materials or equipment. With numerous linkages within and across layers, mapping linkages onto the roadmap resulted in an array of connecting lines that were non-descript, i.e. the connection was not defined, and which made the roadmap look chaotic.

\(^{128}\) Technology development should also be connected to commercial drivers via a linkage grid, not just strategic milestones. This is discussed in 5.4.1.2.

\(^{129}\) See (Waganer et al., 2018) for information on remote handling.
Linkage grids can also be used to connect sub-TGIs. Given the number of sub-TGIs, while identifying and mapping the linkages is arguably important, identifying and mapping sub-TGI linkages would introduce much complexity and would likely require in-depth discussion with experts specialising in each sub-TGI. It was thus concluded that sub-TGI linkages should be the subject of traditional project planning, which could be informed and supported by TGI linkages that were identified, characterised and mapped in the roadmap. Importantly, the decision to avoid sub-TGIs ensured that the roadmap remained a useful tool for exploring future needs and did not evolve into a complex project planning tool that might become cumbersome.

The limitations associated with the use of linkage grids identified a need to adopt suitable software to connect and show as well as update linkages digitally. Moreover, software may ease the burden of updating the roadmap more generally, and the need for roadmapping software is discussed in 5.6.2.

### 5.3.5. The use of TRLs

TRLs, supported by linkage grids, were incorporated into the roadmapping process to understand the required progression of technology. For example, for Tokamak Energy, TRLs were used to define the required state of each TGI at current and for future machines ST-F1 and ST-E1, and thus technology development steps can be planned.\\(^{130}\)

#### 5.3.5.1. Limitations of TRLs

TRLs are designed to provide a metric for assessment of technology progression across different types of technology (Mankins, 1995). In reality, however, applying a generic TRL scale uniformly across all TGIs, even when contextualised to fusion technology development, proved challenging. As such, whilst TRLs are a simple and useful tool, they mask much complexity. For many TGIs, not all steps in the progression from TRL 1 to 9 are the same size. Evans and Johnson suggest that the TRL scale should be considered logarithmic (Evans & Johnson, 2013), i.e. a jump from one TRL to the next requires ~10 times as much effort, i.e. cost and time. Furthermore, the TGIs identified for Tokamak Energy are wide-ranging in scope, with varying complexity and different criteria for “success”. For example, the development of divertor technology (TGI #6) is fundamentally different to the development of physics understanding (and means) to control a burning plasma (TGI #2). Where divertor technology may progress very slowly up the TRL scale via physical testing of hardware, first with testing of individual components and then as the

\(^{130}\) The way in which TRLs supported agile innovation is detailed in 5.4.2.
integration of multiple components, physics-based TGIs may jump from a low TRL to a high TRL quickly due to a breakthrough or validation of theory when a successful experiment demonstrates the theory. Somewhat surprisingly, it is similarly challenging to produce a TRL scale that can uniformly be applied to issues that are perceived to be similar, e.g. HTS magnets (TGI #5) and remote handling systems (TGI #10).

A related issue is the subsequent judgement of the TRL and progression up the scale. TRLs are a subjective form of technology assessment, open to both personal and contextual bias (Ilevbare, thesis). Technologies assessed using a TRL scale are likely to be carried out by experts who may have a skewed view of expected future technology challenges; positive or negative. To remove some bias, individual TRL scales for all TGIs could be developed by individual experts, but then reviewed by consensus including with non-experts to ensure objectivity.

TRLs are not well suited to measure technology progression in which such technologies become integrated. As detailed in 4.3.1, the TGIs for Tokamak Energy are broadly analogous to the technical systems required for a fusion reactor (see Figure 4-10). Each of the technology systems has sub-systems and critical components, many of which exist at a low TRL and must be developed further. However, the notion of introducing sub-TGI linkages created significant complexity. Applying TRLs to different sub-systems (i.e. sub-TGIs) in effect determines the overall TRL for a technology system (i.e. a TGI). Effectively, therefore, TGIs represent System Readiness Levels (SRLs), not TRLs. Adopting a tiered approach to TRLs in this way introduces substantial complexity. This can be illustrated by using the development of one of the many diagnostic tools required for a tokamak (TGI #4) as an example. Independently, a specific component or sub-system of a diagnostic tool may function correctly and thus be adjudged to be at a high TRL. However, when integrated as part of a technology system with other components or sub-systems, it may not perform as it did when tested independently, and there is reassessed to be at a low TRL as an SRL. Continuing with this example, imagine that three sub-systems for a diagnostic (e.g. to measure plasma temperature, see TGI #4) are all at TRL 7 when tested independently. However, when integrated, new and unforeseen problems result in a combined TRL (or SRL) of 3. As such, when integrated as part of a system, the TRL is actually decreased. Development ostensibly is set back, and a new set of challenges must be overcome to progress the integrated technologies to TRL 7 again.

5.3.5.2. Expanding TRLs for assessing commercial readiness

TRLs are also limited in their ability to track commercial progress. TRLs were originally developed for NASA, and thus mission success is considered as demonstrating a technology works at TRL 9. However, the demonstration of a technology at TRL 9 does not
necessarily mean that the technology is commercially viable. For example, in the fusion context, fusion materials (#TGI 9) are being developed to operate in extreme environments. Technical success in the environment required for a commercial fusion reactor could mean a material is at TRL 9, but which simultaneously has been developed whilst overlooking, e.g. cost to manufacture or the supply of natural resources. As such, it is contended that TRLs reinforce the linear model, as they place emphasis on technical success first, and commercialisation later (see 2.3).

NASA developed TRLs as a metric to understand mission success based on the extent to which a technology is tested in the field. It is particularly informative to use the space sector as an example, again. Application to the example of Apollo 11 shows that as the mission successfully put a man on the moon, and the technology developed overcame all technical challenges in doing so, the technology is TRL 9. In the context of fusion, the example of a breeding blanket that is developed to TRL 9, but which costs US$ 5B with further maintenance costs of hundreds of millions of dollars per year, is not commercially ready and thus could not be considered a “mission success”, if commercialisation is the goal. Obtaining a high TRL first, and later attempting to reduce the cost (or overcome other commercial barriers), is not the approach taken by SpaceX or Blue Origin. Instead, these commercially focused organisations are taking the fundamental science behind the technology of space flight – which originated as a scientific (and political) mission – and developing new technology that is not yet TRL 9, but which can be developed to attain TRL 9 whilst also being commercially ready. In other words, SpaceX has not taken a Saturn V rocket and reduced the cost; the company has developed an entirely new rocket system which is only based on the same scientific principles and technologies. Fusion technology can be developed in the same way. To this end, however, TRLs cannot be taken in isolation. To make both space travel and fusion commercially viable, i.e. not a science mission but a business endeavour requires something more than TRLs as a metric.

More specifically, using TRLs as a sole indicator of riskiness is inadequate when trying to understand whether a technology should be pursued, as they do not provide an accurate assessment of innovation risk, i.e. the risk associated with taking a technology to market (Valerdi & Kohl, 2004; Ilevbare, 2014). Therefore, an additional measurement of readiness – an approach to assess “commercial” rather than “technical” readiness – should be considered. Adopting TRLs for innovation has been previously considered by Hartmann and Myers (Hartmann & Myers, 2003). Ilevbare later advanced the idea to develop an aggregated approach which involves considering commercial readiness in conjunction with technical readiness to provide a tool to assess overall technology-to-market risk (Ilevbare, 2014). Here, this combination of the two drivers – technical and commercial – can be construed as constituting an Innovation Readiness Level (IRL). Derived from Hartmann and
Myers, Ilevbare suggests five questions that support the understanding of commercial readiness\textsuperscript{131}:

1. **Value chain**: how ready is the supply chain – e.g. manufacturing, marketing, vendors – to bring the technology to market.
2. **Achievability**: can the technology be developed on time, to budget, and with quality (reliability)?
3. **Enabling technologies**: what is the availability of enabling technology required to support the technology?
4. **Product differentiation**: what is available on the market, i.e. what is the competition?
5. **Market clarity**: what is the market and its readiness to accept the technology?

Necessarily, a scale similar to that required to assess TRL is needed to quantify commercial readiness, i.e. another scale from 1 to 9 that details the progression up the scale towards commercial readiness based on the five questions. Taken alongside TRLs, commercial readiness assessments can be used to produce an aggregated score for overall technology and market readiness (and thus risk), ergo, providing an assessment of the innovation readiness. Integrating such a technique would provide a way to better link technological and commercial perspectives throughout the lifecycle of a technology that is under development\textsuperscript{132}. It could be used as a supporting tool to link the commercial drivers that are developed via PESTLE and SWOT, to the technology (see 5.4.1.2.1).

Adapting specifically to the fusion context, a technology that is at an incredibly early stage of development, is more challenging. It is likely to be more appropriate to deploy at the level of technology systems – for example, to assess the whole tritium breeding blankets, or perhaps core subsystems, rather than at the component level – to understand how to develop technology to be technically and commercially ready, thus achieving successful innovation.

In summary, the use of TRLs introduces significant complexity. Perhaps the best way to solve the issues associated is to ensure that all technologies are planned precisely, and all developed in parallel. However, such an approach would make it easy to become caught up with planning; for which TRLs are not an ideal tool. Instead, the solution should be to gain an understanding of the required technology progression (with the aid of simple TRL scales), combined with an understanding of the desired trajectory (provided by the

\textsuperscript{131} Related to all these contributors is the question of obsolescence, i.e. there is a possibility that a technology becomes obsolete if, for example, the manufacturing supply chain introduces a delay, and a new technology is invented that supersedes it during that delay.

\textsuperscript{132} This links to the concept of value roadmapping by Dissel et al. (Dissel et al., 2009).
roadmap), to proceed with a level of acceptable risk. In other words, planning to enable
testing, to subsequently fail (or succeed) and learn, i.e. agile innovation. However, to
support the development of commercially viable technology, an approach to measure
innovation readiness by using commercial readiness assessments to indicate an overall IRL
should be adopted.

5.4. Roadmapping to support innovation

This section evaluates how the roadmapping method detailed in Chapter 4 supported
innovation per the research objectives in 3.5.3. Contributions and limitations are also
discussed.

5.4.1. Roadmapping to support commercial development

The roadmapping method deployed in this research places particular emphasis on the need
for developing fusion technology whilst also consider commercial drivers to result in
successful innovation: the invention and subsequent exploitation of that invention. The
effectiveness with which the roadmapping method was applied must be analysed.

A roadmap provides a simple way to map an innovation process. There are visual
similarities between the layered, time-based structure of roadmaps and systems innovation
models, such as the chain-link model\textsuperscript{133}. The key difference is that the linkages on the
roadmap are manifested in linkage grids and not visible (without software). The roadmap
structure developed for Tokamak Energy was designed to align with the phases of the S-T-A-M model to show the stages of the innovation process towards fusion commercialisation.
The R&D, engineering and demonstration, and commercial rollout phases were plotted
vertically, and the layers – plotted horizontally – showed the key drivers. However, as
detailed in Chapter 2, fusion start-ups are intended to be on commercial development. A
key limitation of the developed roadmapping process developed is the weaker emphasis on
market-pull. In the first iterations of the roadmap, commercial drivers come only from the
presence of strategic milestones. This limitation must be discussed.

5.4.1.1. Limitations of using strategic milestones as commercial drivers

The strategic milestones layer of the roadmap is simplistic in its function to provide
commercial drivers, as it provides no means to explore or characterise them. Strategic
milestones are typically set by investors and agreed with management. However, feedback

\textsuperscript{133} The chain-link model is used since the innovation organisation model lacks a graphical
representation, which is noted as a major drawback of the model.
from the STIM workshop (see 5.2.2.3) highlighted that a limitation of the roadmapping process was the lack of an explicit layer of the roadmap to assess the market, i.e. a “markets” layer. In consequence, while strategic milestones provide commercially-relevant demonstration targets for technology development, commercial drivers should be accounted for more explicitly.

Fusion start-ups, like all start-ups, exist as part of a larger industrial ecosystem that includes customers, competitors, suppliers and government agencies. Prevailing trends and drivers (such as customers and competitors), as well as future markets and emerging trends, should be understood, as they have a major influence on the internal development of any organisation (Kerr, Phaal & Thams, 2017b; Teece, 2010a; Smith, 2007; Phaal, Farrukh & Probert, 2010). Evaluating the external environment is an imprecise activity. Understanding how internal technology development may affect the market – albeit that in the case of fusion they are long-term and speculative markets – ensures that the organisation is progressing in a direction likely to result in successful innovation (Fitzgerald, Wankerl & Schramm, 2011). Although an assessment of the external environment is to some extent considered in the resources and capabilities layer of the roadmap, e.g. the supply of tritium, which is an issue affecting commercialisation\textsuperscript{134}, there is a greater emphasis on programmatic barriers such as how much tritium can be obtained for experiments, rather than on the commercial drivers explicitly.

5.4.1.2. Introducing a markets layer to the roadmap

Methods and tools exist to support the analysis of the environment in which an organisation sits. These tools are commonly applied to support strategic management as well as for roadmapping, see (Smith, 2007; Phaal, Farrukh & Probert, 2010) and specifically (Brenden \textit{et al.}, 2009). Three tools deemed useful to the application for the developed roadmapping process produced are \textit{PESTLE analysis}, \textit{SWOT analysis}, and the Innovation Matrix.

5.4.1.2.1. \textit{PESTLE analysis}, \textit{SWOT analysis} and the Innovation Matrix

PESTLE analysis is used to identify and assess political, economic, social, technological, legal and environmental (hence PESTLE) external trends and drivers that are external to and thus may affect an organisation (Phaal, Farrukh & Probert, 2010; Newton & Bristoll,

\textsuperscript{134} See Chapter 6.
2013; Smith, 2007) Figure 5-9 provides a list of common factors considered in PESTLE analysis.

<table>
<thead>
<tr>
<th>Political</th>
<th>Economical</th>
<th>Social</th>
<th>Technological</th>
<th>Legal</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Tax</td>
<td>• Movement of capital</td>
<td>• Social and cultural change</td>
<td>• Artificial intelligence</td>
<td>• Domestic law</td>
<td>• Climate change</td>
</tr>
<tr>
<td>• Government policy (ever-changing)</td>
<td>• Alternative markets</td>
<td>• Advertising and PR</td>
<td>• Other computing advances, e.g. modelling and simulation</td>
<td>• International law</td>
<td>• Carbon taxes</td>
</tr>
<tr>
<td>• Regulation</td>
<td>• Competition</td>
<td>• Media</td>
<td>• Smart materials and nanotechnology</td>
<td>• Employment law</td>
<td>• Pollution and emissions</td>
</tr>
<tr>
<td>• Geopolitical issues</td>
<td>• Economic growth</td>
<td>• Education</td>
<td>• Automation</td>
<td>• Nuclear regulation</td>
<td>• Local ecology</td>
</tr>
<tr>
<td>• Limits on international trade (trade war)</td>
<td>• Cost of borrowing (interest rates)</td>
<td>• Consumer attitudes</td>
<td>• The internet</td>
<td>• Health and safety</td>
<td>• Natural disasters</td>
</tr>
<tr>
<td>• Conflict and war</td>
<td>• Investment</td>
<td>• Demographics</td>
<td>• Copyright law, IP and patents</td>
<td>• Cost of borrowing (interest rates)</td>
<td>• Sustainable mining and supply chains</td>
</tr>
</tbody>
</table>

PESTLE analysis identifies and considers the possible influence of external factors on each element of the development programme. Thereafter, if appropriate, development paths can be adjusted to align better with commercial needs or to avoid potential problems or conflicts. For example, an external environmental consideration may relate to the sustainability or availability of particular natural resources required for a fusion reactor, such as beryllium. Materials required for all TGIs could be reviewed to assessed against data on the availability of beryllium, and, if potential problems are identified, alternatives can be sought ahead of the problem manifesting. Consequently, PESTLE analysis could be used to effectively populate the markets layer of the developed roadmap.

SWOT analysis is used to identify and characterise internal strengths and weaknesses and the external opportunities and threats (hence “SWOT”) (Pickton & Wright, 1998). SWOT analysis enables organisations to exploit opportunities, play to strengths, address

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135 PESTLE is also known by several other names, see (Rastogi & Trivedi, 2016).

136 Several aspects of PESTLE analysis already exist in the developed roadmapping process (and roadmap). In particular, external “technological” factors that may benefit internal technology development are considered in the context of open innovation (see 4.3.2.3 and 5.4.3); economic factors are considered in TGI #14; and legal factors (regulation and licensing) are considered in TGI #15.

137 The availability and supply of beryllium, amongst other critical natural resources required for fusion, is explored in-depth in Chapter 7.
weaknesses and counter threats (Smith, 2007; Phaal, Farrukh & Probert, 2010). Figure 5-10 provides a list of common questions asked and factors identified in SWOT analysis.

![SWOT Analysis Chart]

**Figure 5-10**  SWOT analysis to identify strengths, weaknesses, opportunities and threats, adapted from (Brenden et al., 2009; Pickton & Wright, 1998).

SWOT analysis is complementary to PESTLE analysis. The external environment can be assessed in PESTLE analysis and thereafter, the associated opportunities and threats identified compared against internal strengths and weaknesses. Figure 5-11 shows the TELESCOPIC OBSERVATIONS grids which expand SWOT and PESTLE analyses into an integrated and holistic tool that could be used to generate content for a markets layer on the roadmap developed in this research (Panagiotou, 2003).

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138 Smith suggests that the three questions fundamental to roadmapping are linked to SWOT: “where are we now?” is akin to strengths and weaknesses; “where do we want to be?” is akin to opportunities; and “what can we do to get there?” (framed as “what is preventing us from getting there?”) is akin to threats (Smith, 2007).

139 The TELESCOPIC grid generally relates to market analysis, whilst the OBSERVATIONS grid aligns well with aspects of the resources and capabilities layer.
A combination of all the grids described could be used in conjunction with the roadmapping process developed in this research. Given the holistic view of the external environment provided by the tools, they could be used as the primary tool for market analysis. Whilst initially, the tools could be applied at an organisational level, in future, the same tools could be used to identify specific market drivers at the level of individual machines, projects or TGIs. An additional linkage grid would be required to map the findings from market analysis into the roadmap. The *Innovation Matrix* is an adapted linkage grid that could be specifically useful for this purpose. The *Innovation Matrix* is a tool used to plot potential market opportunities in order to identify gaps for potential technology development and understand whether a technology will be “ready” for the market. The *Innovation Matrix* is shown in Figure 5-12. Interestingly, the *Innovation Matrix* includes the time dimension, which is in part due to its origins – it was developed in conjunction with roadmapping (Groenveld, 1997; Matthews, 1991).
The tools described thus far could be incorporated into the existing roadmapping process to enable the generation of a markets layer. The following subsection provides an example of market analysis for a specific application – fusion for desalination – based on the content in the Tokamak Energy roadmap and the ideas relating to markets that have been introduced here.

5.4.1.2.2. Alternative markets for fusion: desalination

For successful innovation, one must first understand potential target markets, i.e. to whom and how a product is sold (Lehtovaara, 2013). Seemingly, the primary focus of the vast majority of fusion programmes, both public and private, including Tokamak Energy, is to focus on electricity generation. Other markets may play to the strengths of the technology and result in a more suitable – or simpler – route to a commercial application (Koen et al., 2001; Chiesa & Frattini, 2011). Fusion is at an early stage of development, and the technology has the flexibility to serve markets other than electricity generation. Fusion start-ups that do not consider potential alternative markets are thus adopting – somewhat ironically – a high-risk approach. Teece notes that the lack of dynamic capability, defined as the ability to respond to market opportunities (see (Teece, 2012)), is behind many of the commercial failures in history, e.g. Fairchild semiconductors ceding to Intel; Nokia to Apple, Blockbuster to Netflix (Teece, 2010b). In the face of a currently transforming electricity generation market, fusion efforts targeting entry into that market are not guaranteed to succeed. However, alternative paths to commercialisation may allow fusion to be strategically dominant over the competition in a given market. Whilst Kulcinski and
Santarius as well as McCarthy et al. consider a range of alternative fusion commercial products (Kulcinski & Santarius, 1998; McCarthy et al., 2002a), and Nuttall et al. consider hydrogen production via a “Fusion Island” concept (Nuttall, Glowacki & Clarke, 2005). Here, fusion for desalination is considered\(^\text{140}\).

Different commercial applications will place different performance requirements on the development of a fusion reactor. It is well understood that an electricity-generating fusion power plant requires a require high net energy gain (\(Q_{\text{fus}}\)). The criteria for an electricity-generating power plant also requires energy generation systems, particularly the breeding blanket, to operate high temperatures for increased efficiency over the existing competition, e.g. fission reactors. Electricity generation – most likely\(^\text{141}\) – also requires control of long duration plasmas, to avoid being considered an “intermittent” energy source (as is a common criticism of conventional renewables). Plasmas operating for long durations, in turn, require plasma-facing materials to have high temperature and neutron damage thresholds to increase the lifetime of components and avoid downtime for maintenance.

A fusion reactor for desalination may be able to avoid such drawbacks. Firstly, a plasma of low \(Q_{\text{fus}}\) might be acceptable, as the energy supplied to create the fusion reaction is not important; it is the heat that is the commercial product. Desalination does not require continuous plasma operation; it can be pulsed (thermal fatigue cycling permitting). Blankets can be designed to handle temperatures of approximately 300 °C, rather than at higher temperatures that are required for high-efficiency electricity generation (Hooper, 2018). Finally, there are benefits of fusion for desalination over the existing competition on the market. Fission reactors produce high-level nuclear waste; fossil fuels produce carbon emissions; and conventional renewables (excluding – perhaps – concentrated solar power) are typically expensive and inefficient.

Simpler design and performance requirements may open a near-term commercial pathway for fusion. Despite potential benefits, however, there are some similarities between fusion for desalination and for electricity generation that cannot be avoided, i.e. fundamental features that are required irrespective of the commercial application. For example, a functional divertor must still be developed, reactor components must be manufacturable, and the production of large quantities of radioactive waste should be avoided where possible. Importantly, this indicates that regardless of commercial application, there are certain technologies that must be developed on the critical path. Accordingly, if technology

\(^{140}\) Fusion for desalination has recently been advocated by Hooper, see (Hooper, 2018). This research specifically considers the market aspects, but naturally some of the ideas overlap.

\(^{141}\) Here described as “likely” as there are some concepts that embrace pulsed systems for electricity generation, such as General Fusion (General Fusion, 2019).
development can be aligned appropriately with a range of potential commercial applications, the final fusion product, i.e. a FOAK, may be able to serve multiple markets and doubling down on a prospective future market can be avoided.

In summary, early-stage market analysis – aligned with technology development using a technology roadmap and linkage grids – can provide an important tool to ensure the development of commercially viable fusion. Moreover, exploring potential new applications may allow start-ups to change direction or to develop spin-offs that can exploit entirely new markets.\footnote{Incidentally, TAE Technologies (see Table 2-1), has established “TAE life sciences” as a spin-out focused on medical applications of its fusion technology.}

5.4.2. **Roadmapping to support agile and lean innovation**

The application of the roadmapping method was intended to adhere to agile (and lean) principles. This section will evaluate how the developed roadmapping process supported agile and lean innovation.

5.4.2.1. **Changing requirements and future challenges**

Agile innovation necessitates rapid cycles in which changing requirements are embraced, and changes can be implemented into the next iteration (see 2.5.7). The roadmapping process was used to continually assess the route ahead. Any new or conflicting requirements captured in the roadmap can then inform a change in direction, which can be aligned with the development cycle. For Tokamak Energy, the roadmap thus acted as a supporting tool to guide technology planning, whilst not disrupting current experiments and technology development activities.

5.4.2.2. **A fusion Minimum Viable Product (MVP)**

Via TGI analysis, in particular, Tokamak Energy could identify, eliminate and avoid wasted time and resource on activities that were judged not to be important to the mission. This is aligned with lean innovation (2.5.5). However, the identification of the critical path to a fusion MVP was in itself a key part of the roadmapping process. In 4.1.3, Tokamak Energy’s MVP, i.e. ST-E1, was outlined. An MVP must demonstrate the core features of the technology whilst scaling a commercial product (Ries, 2011). Specific “MVDs” were identified for Tokamak Energy and plotted as strategic milestones on the route to the MVP. MVDs represented target milestones that should be reached as fast and as cheaply as possible. The roadmap, in particular through the use of the linkage grids and TRLs, helped
to identify the high-level requirements of machines and subsequently of TGIs to achieve each MVD milestones. Noting that each MVD must lead to the next, and thus long-term requirements must be considered even in the near-term, the roadmap supported the alignment of technology development activities with the MVDs to outline a critical path for the company. All activities not on the critical path – some of which were indirectly important – were avoided. The alignment to the critical path thus supported focused project planning and avoided waste, whilst planning future development cycles. If and when strategic milestones, or indeed technology setbacks and breakthroughs alter the view of the future, the roadmap can be used as a dynamic tool to capture the changes and to change the critical path.

5.4.2.3. Parallel development

The roadmap breaks the numerous TGIs into distinct streams on the roadmap. Each stream shows the steps forward, required progression to meet milestones and highlights the method of resolution for key tasks. If the risk is high, then multiple options being developed in parallel may be necessary. For instance, for Tokamak Energy, different prototype divertors were identified for ST-40. Rather than deciding on one design, the roadmap allowed for all to be developed in parallel until a critical point at which the optimal option can be chosen, when more information is known. This avoided wasting time and resource in the long-term, as it reduces the risk of only developing one design and later having to change direction. For some technologies, it may be appropriate to engage with the decision to single out one technology early on. In either case, the roadmap shows that all development streams must be progressed in parallel.
5.4.2.4. **Emphasis on teamwork**

A key principle of both agile and lean innovation is that development is carried out by semi-autonomous groups in which individuals are empowered and encouraged to contribute new ideas. Particularly through focus workshops (4.4.3), but also through review workshops (4.4.2), individual participants are able to contribute to a particular area of expertise to the roadmap. For instance, in a focus workshop with an engineering consultant on divertor technology (TGI #6), the consultant identified optimal design parameters which were captured in the roadmap to be reviewed in the next review workshop. The roadmapping process was suitably designed to elicit ideas and leverage knowledge from a highly skilled workforce that may benefit the company or the development programme.

5.4.2.5. **Visual aspects of roadmapping**

This research has placed additional emphasis on constructing a visually useful roadmap as an important part of the process. For this purpose, additional roadmap visualisations have been developed for communication, which emphasises the ability of a roadmap to portray a “visual narrative of strategic intent”\(^{143}\). Whilst communication is discussed in depth in 5.5, visual aspects of roadmaps are also relevant to agile and lean innovation. Many practical methods for both agile and lean innovation place focus on visual boards for management, see (Caetano & Amaral, 2011). Quite simply, the roadmap developed at Tokamak Energy became a central tool and a platform for discussions in focus workshops and review workshops, but also as a reference document in day-to-day meetings. As such, it is contended that the roadmap as a visual artefact is – in and of itself – a tool to support the implementation of agile and lean innovation.

5.4.2.6. **Limitations**

Whilst roadmaps show the steps ahead; they cannot “do”. By extension, roadmaps thus cannot carry out a “build-measure-learn” cycle. If designed to be updated in line with agile build-measure-learn cycles, the process of roadmapping can help identify what is needed by capturing the learning from the previous cycle and evaluating the needs of the next (and of future cycles), as detailed in 4.7. However, in applying agile innovation to the fusion hardware context, cycles are necessarily longer than in software. Judiciousness – rather than expediency, as with software – in planning technology development cycles naturally results in longer cycle times. In consequence, if a roadmap is updated to align with agile build-measure-learn cycles, it will only be updated once a year or so, whilst an agile software

\(^{143}\) Thanks to Dr Robert Phaal for this definition.
roadmap may be updated once every quarter (for example). One observation is that – perhaps naturally – the slower progress of development in a fusion start-up compared with software; whilst both in their own context can be considered “fast”, meant that the roadmapping process was not seen as an everyday activity but more as a tool to support long-range planning from time-to-time. This is further discussed in 5.6.1.2.

5.4.3. Roadmapping to support open innovation in fusion start-ups

Fusion start-ups lack the research capability, financial and human resources, and credibility of large public fusion programmes. Often, they are compelled to seek external partners for support (Teece, 2010b). Start-ups can leverage the experience and/or skills of the collaborator, save on costs by bringing in external ideas, and improve their credibility by working with other, often well-established institutions or organisations. Moreover, start-ups can benefit from such partnerships due to simpler organisational structure and the ability to adapt (Van de Vrande et al., 2009; Spithoven, Vanhaevertbeke & Roijakkers, 2013; Brunswicker & Vanhaevertbeke, 2015; Parida, Westerberg & Frishammar, 2012).

5.4.3.1. Consultants and innovation orchards

Bianchi et al. find that consultants, in particular, can result in significant value to a company at a relatively low cost (Bianchi et al., 2016). In particular, formalising the involvement of consultants may increase the proficiency of the firm in scouting and identifying collaborators through networks (Brown & Eisenhardt, 1995; Ernst & Kim, 2002; Bidault & Fischer, 1994). At Tokamak Energy, focus workshops were set up with expert consultants to develop content for the roadmap, but also to identify potential collaborators from the consultants’ network. In determining a method of resolution for given activities, consultants often identified potential collaborators from their networks. In collating views of numerous consultants, a portfolio of prospective collaborators can be developed, effectively creating an innovation orchard for the company (see 4.3.2.3 and (Singer & Bonvillian, 2017)).

5.4.3.2. Open innovation to support internal development

In assessing future challenges during the roadmapping process, gaps are naturally identified. The following questions can help to characterise a gap:

1. Is the gap on the critical path for the company?
2. Is the gap a “general” gap (i.e. the solution is not known by anyone) or is the gap known or understood, but the solution not available to the company?

If a technology is on the critical path for the company; if existing external activities do not meet the need; or if internal activities are needed to exploit a commercial opportunity
through the generation of IP (such as HTS magnet development), then bringing the technology development in-house is necessary. However, some activities are too expensive to undertake, either due to high complexity or cost, i.e. areas in which gaps are on the critical path, and a solution exists but is not owned, known or understood by the company. In such cases, collaborative development – and open innovation – is necessary and valuable. This is especially true in areas in which a company does not have the expertise to explore, or in areas that it is unlikely to ever bring in-house due to the cost or complexity, or – in the case of fusion – where there is substantial pre-existing external R&D ongoing (e.g. development of advanced steels)\(^ {144}\). Effectively, by understanding which areas to collaborate on, which to do in-house, and also in which to import solutions or ideas from existing public programmes, fusion start-ups can avoid wasting time, money and effort on areas in which there is already expertise. In this regard, the roadmap – by way of the methods of resolution – can further support start-ups to adopt a lean innovation approach.

5.4.3.3. Combining Open Innovation and Intellectual Property

Core technology protection mechanisms are typically achieved through a mix of IP and trade secrets (know-how). IP protection mechanisms such as patents are fundamental to avoid the risk of technology misappropriation, but – based on the observations from this research – open innovation and retention of industry knowledge or protection of IP are not necessarily mutually exclusive. It is possible to simultaneously adopt an open innovation approach whilst remaining protective of central IP. In fact, each can facilitate the other. Knowledge of which activities to bring in-house, and which to collaborate on, based on the potential value of the knowledge is built into the structure of the developed roadmap. If constructed carefully to avoid revealing confidential information, parts of a roadmap can be shared with collaborators to facilitate joint R&D. For instance, Tokamak Energy could create a “collaborator” roadmap (refer to “design project with company W” on TGI #7 in Figure 4-17), to share all relevant and non-confidential aspects of the plan. As such, the roadmap can become a tool to support knowledge management\(^ {145}\) and to reduce

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\(^{144}\) This is also aligned with the SpaceX approach. SpaceX is building IP and know-how in certain technology areas and depending on future partners to develop technology solutions to future problems it is yet to (or cannot) tackle, but which have been identified. See (Rigby, Sutherland & Noble, 2018).

\(^{145}\) Knowledge management (or knowledge governance) pertains to the control of knowledge and the mechanisms by which that knowledge is created, integrated and shared across an organisation or system (Foss & Michailova, 2009).
information asymmetry\textsuperscript{146}. How this research contributes to knowledge management and information asymmetry is further explored in the context of communication in 5.5.4.2. However, in the context of open innovation, a roadmap is a tool to support the understanding of what – and how much – information should be shared, i.e. it is a knowledge management tool. In the context of collaborative development, information asymmetry should be avoided without giving away strategic position. Using a roadmap as the communication tool can facilitate a reduction in information asymmetry. Figure 5-13 illustrates how information asymmetry typically exists, and Figure 5-14 shows how it can be avoided by selectively sharing specific information using a roadmap.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5-13.png}
\caption{An example of typical information asymmetries between a company and a collaborator, recreated by the author based on the diagram in (Anderson & Lyall, 2013).}
\end{figure}

\textsuperscript{146} Information asymmetry derives from economic theory in which one party has more or better information than the other in a transaction and thus can control the information that the other party (or parties) sees. An example of information asymmetry is “insider trading”, see (Bergh et al., 2019; Meckling & Jensen, 1976; Akerlov, 1978).
5.4.4. Limitations: Quantitatively measuring innovation

One limitation of this research is that measuring the effectiveness of the roadmapping process using quantitative metrics was not considered. A tool that could be used to measure innovation is the Key Performance Indicator (KPI). A KPI represents an objective and in some way, measurable quantity that can gauge progress (Durkacova, Lavin & Karjust, 2012). Using multiple KPIs as a metric for measuring innovation performance is not simple. It is particularly difficult to measure innovation in a start-up environment as development is rapid and non-linear. Quantifiable KPIs such as “lead time”, “sales growth” and “return on investment” can be used to measure innovation in an established organisation that operate reliably and have historical performance data. For start-ups, KPIs instead have to be suitable for measuring innovation at the front-end of the innovation process where such data aren’t available. Various KPIs that could be adapted to assess the effectiveness of innovation in the fusion start-up context have been explored (Sawang, 2011; Choi & Ko, 2010; Cascajo & Monzon, 2014; Banu, 2018; Brattström et al., 2018).

One particularly useful innovation KPI could be to measure the time taken to perform one cycle of build-measure-learn for a specific TGI, i.e. to measure the “speed of testing” (or indeed the “speed of learning”). However, to understand the effect that roadmapping might have on innovation using this KPI would require a period of time before roadmapping was implemented to gather data to compare against results after implementation. However, as

Figure 5-14  Information asymmetry with knowledge gap reduced by strategic sharing of information using a roadmap, recreated by the author based on the diagram in (Anderson & Lyall, 2013).
start-ups typically scale up rapidly and – as noted – non-linearly, it would be difficult to generate representative historical data. The lack of a quantitative measure to gauge the effectiveness of the roadmapping represents a limitation of this research.

5.5. **Roadmapping to support communication**

This section evaluates how the roadmapping method detailed in Chapter 4 supported communication per the research objectives in 3.5.3. Contributions and limitations are also discussed.

5.5.1. **For internal communication**

The way in which the roadmap and process to develop supported internal communication is evaluated.

5.5.1.1. **In review workshops**

Review workshops provided a dedicated space for the discussion of the company’s future, and to build a consensus on a path forward. As observed by Kerr et al., workshops create environments in which participants can push the boundaries of their own knowledge, creating overlaps for joint idea creation (Kerr, Phaal & Probert, 2012). For example, a TGI expert and a project manager, both viewing the same roadmap, will have different priorities and different perception of which problems are the largest. Typically, scientists and engineers have a very different view of the future to managers and entrepreneurs. Technical staff want to see their invention succeed, whilst managers are focused on a route to market (Freeman & Engel, 2007). Of course, both are necessary, and both are shown on the same roadmap, even if it is interpreted differently. As such, review workshops provide a space for cross-cutting discussion of priorities, ideas and concerns. Whilst some interactions will see an overlap of ideas or even a conflict in priorities, all interactions result in the sharing of knowledge that can result in generation of new ideas and – eventually – a consensus. A roadmapping workshop thus allows knowledge sharing to be carried out in a dedicated space, in a structured way, using the roadmap for necessary context and with the ability to record the new information or knowledge being shared (see 5.5.4 for discussion on roadmapping to support knowledge management).

The questions shown in Table 5-8 have been developed based on observations of the process at Tokamak Energy which typify what might be asked by specific individuals using the roadmap for communication as a contribution to the existing communications literature. The questions are written from the perspective of different stakeholders all viewing the same roadmap.
<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Typical question</th>
</tr>
</thead>
</table>
| Executive or high-level commercial manager | - Are we likely to be able to present results on TGI #4 to show our progress towards meeting our strategic milestone by the end of the year?  
- What are the key unknowns that may affect the critical path to deliver machine B?  
- What are the major constraints and the cost of altering our design to be suitable for desalination rather than electricity generation? |
| Technical manager | - Where can we cut R&D costs on project alpha?  
- How many staff are required to deliver the technical plan for TGI #6 over the next two years?  
- What TRL do we need to achieve on TGIs #4 and #5 to achieve machine B? What does the progression of these TRLs look like over time – how much resource is needed to deliver it, and have we missed anything that we need to budget for? |
| Technical expert | - What are the results of the latest on the physics publications associated with public programme X on sub-TGI #1.2, and can we work with collaborator Y to analyse these?  
- Have we considered “X” and “Y” technical issues on TGI #9?  
- Should we consider whether it is worth pursuing a novel solution that I came across for TGI #7 at a recent technical conference? |

**Table 5-8** Typical questions from different stakeholder groups using a roadmap for communication inside an organisation (mock-up questions; technical detail redacted).

Despite review workshops providing a space for general discussion of all key issues, Kappel notes that staff within an organisation have limited interest in issues not relating to their own area of operation or expertise (Kappel, 2001). As detailed in 4.4.2.2, a key observation of the first workshop at Tokamak Energy was that in-depth technical discussions not relevant to the roadmapping activity caused interference. In consequence, and due to the large number and complexity of technical issues, focus workshops were introduced into the process to leverage knowledge and ideas from experts\(^{147}\). Even though technical experts were still involved in the workshop, the rationale was to ensure that technical experts had a voice. Focus workshops provided a license for technical experts to provide comments freely and for information that could feed directly into the roadmap.

5.5.1.2. **Within the organisation**

The technical roadmap also supported general technical communication inside the organisation for those not involved with its development. However, while features of the technical roadmap were designed to help navigate it, as described in 4.5.1, extracting

\(^{147}\) Leveraging knowledge from subject matter experts (via focus workshops) is discussed in 4.4.3.
information from the roadmap is not intuitive for someone not involved in its design. Therefore, it may be effective to produce a roadmap to support communication to broader internal audiences. It could retain the same features as the technical roadmap (Figure 4-17), but the layout could be simplified. Such a roadmap could be used to elicit ideas or feedback from all staff.

Whilst providing employees with a broader understanding of the organisation's mission and vision, and eliciting feedback; an internal communications roadmap would also be able to show company staff where their contribution fits in within the organisation's future plan. Pierce et al. find that when staff are given information about the mission of an organisation, its goals and performance, they can develop psychological ownership to it, which can lead to an enhanced sense of purpose or responsibility (Dipboye, 1977; Korman, 1970). As a result, staff are likely to promote change and work towards a goal if they feel they can make a tangible impact (Pierce, Kostova & Dirks, 2001; Dirks, Cummings & Pierce, 1996). Pierce et al. present the open-ended research question: how can psychological ownership be facilitated in organisations? (Pierce, Kostova & Dirks, 2001) It is contended here that the Tokamak Energy roadmap, which presents a holistic view of the future plan of the organisation, but whilst importantly including each aspect of the required development, be it a specific technology or a perspective on supply chain or investment, can allow staff to understand their contribution and can thus support psychological ownership.

5.5.1.3. Potential visualisations to support internal communication

A suggestion from the STIM workshop was for other visualisations to be developed using information from the roadmap (see Table 5-6 and Table 5-7). A set of additional roadmap visualisations that may be effective for internal communication are provided in Table 5-9 as a contribution to the roadmapping literature.

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148 A participant at the STIM workshop also made this comment, as detailed in Table 5-7 in 5.2.2.5, but it related to the communications roadmap rather than the internal roadmap.

149 Psychosocial effects are explored in the context of roadmapping in (Kerr, Phaal & Probert, 2012).
<table>
<thead>
<tr>
<th>Visualisation</th>
<th>Description</th>
<th>Audience</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IP Roadmap</strong></td>
<td>Showing IP opportunities that have been identified, <em>e.g.</em> for TGI #10 (remote handling)</td>
<td>Commercial manager</td>
</tr>
<tr>
<td><strong>Supplier roadmaps</strong></td>
<td>Detailing information useful for suppliers, <em>e.g.</em> for HTS suppliers</td>
<td>Suppliers and collaborators</td>
</tr>
<tr>
<td><strong>TGI roadmaps</strong></td>
<td>Specific TGI roadmaps to show all technologies, machine, project, market and resource aspects that are connected to that TGI, <em>e.g.</em> TGI #11 (tritium handling) roadmap could show the expected quantities and costs of tritium for ST-F1 (in resources layer), as well as links to materials TGI #9 (materials) and TGI #15 (licensing and regulation).</td>
<td>R&amp;D managers, project managers, TGI subject-matter experts</td>
</tr>
<tr>
<td><strong>Cost roadmap</strong></td>
<td>Showing estimated cost of certain machines, projects or TGIs, <em>e.g.</em> show the cost of developing a first wall material over a 5-year period</td>
<td>Executives, company board and investors</td>
</tr>
<tr>
<td><strong>Competitor roadmap</strong></td>
<td>Showing the milestones and achievements of competitors, <em>e.g.</em> Gen IV nuclear power</td>
<td>Executives, company board and investors</td>
</tr>
<tr>
<td><strong>Network diagram</strong></td>
<td>A network diagram showing roadmap linkages, i.e. a visual representation of what is shown in linkage grids</td>
<td>R&amp;D managers and commercial managers</td>
</tr>
</tbody>
</table>

**Table 5-9**  
Additional roadmap visualisations to support communication.

5.5.2. For external communication

5.5.2.1. With public audiences

The Tokamak Energy communications roadmap, as shown in Figure 4-20, was created for the purpose of public communication of the company’s plan, vision and key steps. The communications roadmap features in all external company presentations and has been used in investment pitches; at conferences; for public outreach events and is displayed on the home page of the company website\(^\text{150}\).  

Participants at the STIM workshop provided several useful comments relating to the communications roadmap, see Table 5-7. In particular, one participant noted that it was unclear why the diagram converged on ST-F1, as Tokamak Energy’s Wright Brother’s moment. As detailed in Chapter 2, ST-F1 marks the fusion’s Wright Brothers moment. The

\(^{150}\) Refer to “mission” in (Tokamak Energy, n.d.).
divergence of the funnel after ST-F1 shows the expansion of opportunity that is expected after technical feasibility of fusion is demonstrated, i.e. an increase in investment, scientific interest, and the number of possible commercial applications.

Another participant noted that the communications roadmap provides a “Segway” to probe deeper about certain elements of the roadmap, starting from a basic level. This raises an important point for discussion. Whilst the communications roadmap reflects the internal roadmap, those viewing it are not necessarily aware of that fact (Zurcher & Kostoff, 1997). Public communications roadmaps, therefore, risk perpetuating information asymmetry, i.e. communications roadmaps can show a “marketing” lens. Attempting to influence public audiences who don’t necessarily have a shared understanding carries the risk of creating unrealistic expectations. Without adequately conveying the realities, public opinion can only be based on the positive image presented, and the accomplishments of the mission will be continually judged from this reference point (Cooper, 2003). Accordingly, care must be taken in conveying a roadmap that displays the intended mission and that it is accurate rather than a marketing tool. The communications roadmap developed at Tokamak Energy is transposed from the internal technical roadmap and shows the future as it is currently envisaged\(^\text{151}\).

5.5.2.2. With investors

The public communications roadmap can also be used to support discussions with investors. Investors must be convinced that high front-end risk associated with the development of fusion will ultimately result in an ROI. Existing investors – who can also be shown the internal roadmap – can use higher-level communications roadmaps to probe about specific challenges and opportunities on the path ahead. By discussing commercial goals, timescales, as well as specific technology development, investor-driven scenarios could – in theory – be mapped onto a roadmap to understand the high-level programmatic impact of those ideas. As such, a roadmap can facilitate shared decision making between investors and company management\(^\text{152}\).

Linkage grids that connect the layers of the roadmap are also useful in communicating with investors. Investor-set strategic milestones are connected to technology development as well as the resources – e.g. investment – required to deliver on the milestones. While

\(^{151}\) Also see 8.6.1.

\(^{152}\) In the development of the risk roadmap for Tokamak Energy – shown in Figure 4-19 and discussed in 5.5.3 – two versions of the technical roadmap were created in order to develop accurate information to populate path “A” and path “B” risk roadmaps to show to investors.
investors cannot provide an endless stream of capital and they are averse to programmes which consistently slip, a frequently updated roadmap can provide a realistic assessment to moderate investor expectations, particularly in setting strategic milestones. Naturally, if investors respond by deliberately setting challenging milestones, then the roadmap can work in reverse, i.e. technology development aligned to deliver on the milestone, but often with the caveat that more investment is needed!

5.5.3. For uncertainty and risk

As characterised in Chapter 2, a key difference between fusion start-ups and public fusion programmes is in the approach to risk. Fusion start-ups must proceed with risk if they are to accelerate development. However, whilst a level of risk is unavoidable, and speed and cost are important, fusion start-ups should conduct due diligence to understand which path (or paths) might present the best chance of success. The process of roadmapping can be considered as a tool for planning in conditions of uncertainty, and which can be used to identify potential programmatic risks and opportunities associated with a particular future path. However, a roadmap is not a tool to resolve identified uncertainties to reduce risk, but rather a tool to assess those risks. This is demonstrated by the “risk roadmap” shown in Figure 5-15, developed by Albright and Kappel, which identifies and plots key programmatic risks by identifying the consequence (i.e. the severity) and the likelihood of each risk occurring.

![Figure 5-15](image.png)  
*Figure 5-15  A risk roadmap to identify key risks to success, reproduced with the permission of Taylor & Francis publishing from (Albright & Kappel, 2003).*
For Tokamak Energy, a similar risk roadmap was developed principally to facilitate dialogue between management and investors, as a tool to communicate the relative risks of pursuing one of two paths. Successful risk communication involves managing stakeholder expectations to “raise the level of understanding of relevant issues or actions for those involved [in order to] adequately inform[ them] within the limits of available knowledge” (Council, 1989). Each of the two paths shown on the relative risk roadmap for Tokamak Energy – “A” and “B” – comes with some level of risk; as before, it is unavoidable. Path “A” had higher technology risk but presented a route that is potentially lower cost and faster; path “B” had lower technology risk but presented a route that is potentially higher cost and slower. Each path has risks associated with it. The technological uncertainty on the faster path could result in a mechanical failure that requires a great cost to fix, and the slower path presents a risk that the company could be overtaken by faster, less risk-averse competition. In particular, the use of traffic lights can show expected progression through TGIs, the associated resource requirements and – importantly in the context of the audience of this visualisation (investors) – the capital required. The risk roadmap thus facilitated the decision-making process at Tokamak Energy in selecting and agreeing on a path forward.  

5.5.4. Roadmapping for communication to support knowledge management

Many aspects of roadmapping for communication relate to knowledge management. As detailed briefly in 5.4.3.3, there are knowledge boundaries between staff within an organisation, across a sector, and external to both the organisation and the sector. Internally, there is a boundary of knowledge between, for instance, a commercial manager and a subject matter expert. Externally, there is a boundary between a technical manager and an investor, for instance. Based on observations from this action research, this section explores how roadmapping can be used to capture and display information across such boundaries; specifically, how it can be used to support knowledge management and information asymmetry (see footnote 145 and 146). There are two important considerations relating to roadmapping and knowledge management. Firstly, how a roadmap (and the roadmapping process) can be used to extract knowledge from key individuals providing unique perspectives; and secondly, how a roadmap can subsequently be used to communicate that knowledge. The first relates to the process of SECI and Ba, and the second relates to information asymmetry and boundary spanners.

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153 For a perspective on risk and investment, specifically in the context of fusion start-ups, see (Rothrock, 2016).
5.5.4.1. **SECI and Ba**

The creation of knowledge is dynamic and must be managed. A roadmap is a physical space to capture, maintain and exploit information and knowledge. However, there is an important distinction between the definitions of “knowledge” and “information” that must be established for this context. Information here relates to processed data, whereas knowledge is information that has been applied to a given context. In particular, knowledge is related to experience and is often tacit. The theory of how tacit knowledge can be created and translated into explicit knowledge (i.e. information) to be shared is characterised by the SECI process (Nonaka, Toyama & Konno, 2000). A roadmap in some ways exhibits the SECI process, as it provides a platform for different perspectives, ideas and thus knowledge to be shared as information. The sharing of knowledge in a specific context is defined by the theory of “Ba”; a Japanese word roughly translating to “place”, the central part of the theory of Ba is that knowledge creation happens in a specific context, i.e. a place (Nonaka, Toyama & Konno, 2000). When combined, SECI and Ba can be defined as knowledge creation through the conversion of tacit to explicit knowledge in a specific context (or place). SECI and Ba are shown in Figure 5-16 and Figure 5-17, respectively.

![SECI matrix](image)

*Figure 5-16  SECI matrix showing the process of tacit to explicit knowledge conversion (and vice versa), reproduced with permission from (Nonaka, Toyama & Konno, 2000).*
In management research, there are multiple techniques that can be used to translate the theory of SECI and Ba into practice. A roadmap represents a particularly useful practical application of SECI and Ba as it provides the means to create and share knowledge—typically, in a workshop—and in a specific context, i.e., using the roadmap for context. The ways in which SECI and Ba overlap with roadmapping has already been explored by Kamtsiou et al. (Kamtsiou et al., 2006). With reference to existing literature, insights from the application of roadmapping in this research can be used to further understand roadmapping as a tool and technique to turn theory into practice.

An important aspect of Ba is to build and maintain places of interaction and to support that space by using tools to bring together groups to create shared knowledge (Kamtsiou et al., 2006). Roadmapping workshops implicitly reflect Ba. Kerr et al. note that the “population of the roadmap [...] with the sticky notes containing participants’ ideas is initially a knowledge-sharing process” (Kerr, Phaal & Probert, 2012). As such, whilst review workshops have been previously analysed in the context of SECI and Ba, and also in (Kamtsiou et al., 2006), the incorporation of TGI analysis and focus workshops for knowledge creation and sharing is a novel addition of this research. TGI analysis was used to translate explicit knowledge, e.g., in the form of journals or reports, into contextualised information useful for Tokamak Energy. However, knowledge is not only limited to codified documents, reports and experiments but also in tacit knowledge that resides in the minds of individuals, typically experts (Nonaka, Toyama & Konno, 2000; Kamtsiou et al., 2006). Focus workshops functioned to leverage such tacit knowledge from experts into explicit information, i.e., in a format that can be absorbed by others in order to both inform the future planning and to facilitate knowledge transfer within the company. In both instances, the information that
percolates into the roadmap can – referring once more to the SECI process in Figure 5-16 – be translated back into tacit knowledge and communicated to another member of the team, either through dialogue or through viewing the roadmap and associated documents. Effectively, therefore, the roadmap can be the “place” to translate knowledge from tacit (from experts) to explicit (in the roadmap).

5.5.4.2. Information asymmetry and roadmaps as boundary spanners

A roadmap can facilitate communication between all stakeholder groups to counteract the effects of information asymmetry if used appropriately. The origins of information asymmetry are from economic theory (see footnote 146). However, as noted, information asymmetry can be applied to the context of communication, i.e. the asymmetrical exchange of information. In particular, and as discussed in 5.4.3.3, a roadmap can be a tool to manage and control what information should be understood, and by whom. Naturally, the information shared at each level of an organisation – or outside of it – should be proportionate with the role that each actor plays in the system. In the example of communication with a collaborator, information asymmetry is intentional for the perceived need to protect interests, and it is thus for a strategic purpose. Another example of necessary information asymmetry, albeit not for strategic purposes, is that a plasma physicist is not concerned with the supply of tritium; just that tritium is available for experiments. Similarly, the concerns of a senior technical manager are necessarily very different from that of a technician, collaborator, and an investor etc. However, some information asymmetry can also be unintentional, i.e. where there is a difference in understanding of a particular situation due to one party being privy to information and the other not, which can result in a number of undesirable effects.

At Tokamak Energy it was observed that information asymmetries could manifest in a variety of ways. It can exist internally between, for example, the CEO and a technical manager, in which there is an asymmetry in the understanding of time and resource needed for a project. The technical manager may have a better understanding of the technical problems, but the CEO has a view of the organisation’s targets (i.e. its strategic milestones). In this scenario, a roadmap can be used to reduce the asymmetry that exists between the two actors, to find a consensus that satisfies both parties. Or, in the case of engineering systems, which reduces information asymmetries to reveal the “truth”, e.g. a scientist can communicate information regarding the thermal limit of a material that a CEO may not be aware of, but which underpins a strategic request made to them by an investor. The roadmap can then become a tool to support such discussions and to potentially map out a strategy that can be agreed by both parties. In the case of external information asymmetry, a roadmap can be used to reduce information asymmetry between a manager and a prospective investor. Lajara and Macada indicate that investors may “charge more” (i.e. 205
invest less) to negate the risk of “not knowing” (Lajara & Maçada, 2013). A roadmap can thus be used to build understanding and – ultimately – a level of trust across the organisational boundary, which may result in, for example, increased investment by an investor.

Methods or techniques to overcome information asymmetries can be described as “boundary spanners”; tools and techniques that broker trust and identify, translate and relay information between functions (see (Tushman, 1977; Keller & Holland, 1975)). Kerr et al. suggest that roadmaps can be “boundary spanners” (or “boundary objects”), particularly because of their layered architecture and collation of perspectives (Kerr, Phaal & Probert, 2012). The roadmap produced for Tokamak Energy has demonstrated its utility as a boundary spanner, and it has also facilitated specific people within the company to themselves act as boundary spanners. For instance, technical managers involved in the development of the roadmap can report back to their teams to communicate the overall plan of which they are a part. In particular, through the use of linkage grids, individual technical teams can identify and understand where their work has cross-links and/or conflicting requirements. Externally, the communications roadmap has provided Tokamak Energy with a boundary spanner to communicate its mission with public audiences.

5.6. Other observations

This section analyses and discusses observations made during the development and implementation of the roadmapping method in this research.

5.6.1. Challenges with roadmapping as a method

Limitations in design and application of the roadmapping method specified in this research have already been explored in this chapter, especially the need for an explicit markets layer (5.4.1.2) and tools to support the process, in particular TRLs (5.3.5) and linkage grids (5.3.4). However, other limitations and challenges were observed during the course of this research that related to roadmapping as a method rather than the application or design. This sub-section analyses and discusses the limitations of the roadmap, specifically relating to embedding roadmapping within Tokamak Energy.

5.6.1.1. Embedding roadmapping in an organisation

Most roadmapping processes follow a sequence of initiation-development-implementation (Gerdsri, 2007). This sequence is reflected in the diagram that shows the roadmapping process developed for this research (Figure 4-9). When a roadmapping process has been created and developed, it must be embedded into an organisation to enable it to have
ongoing use. However, embedding must be managed throughout the roadmapping process, even though it appears an activity that should be tackled during the implementation phase. In the early stages of the roadmapping process at Tokamak Energy, embedding issues were considered, principally: to involve management to ensure that the scope, focus, format and intended outputs of the roadmap to be developed were suitable. In the development phase, the process was adjusted in line with company needs, and supporting tools and techniques were introduced to the process as necessary. In the implementation stage, the process was designed to be handed over by the researcher to the company. At each phase of the process, different approaches were deployed to support embedding, guided by ideas from (Kappel, 2001; Albright & Kappel, 2003; Gerdsri, 2007).

Firstly, a senior “champion” – for Tokamak Energy, the CEO – supported the roadmapping activity and communicated this support to the rest of the company. Secondly, and relatedly, staff were educated on the purpose and usefulness of the roadmapping process. Several presentations were held with key members of staff early in the process and, on one occasion, a presentation was given at a meeting involving all company staff and consultants. Finally, because the research involved the researcher embedded within the organisation, it was determined that in the later stages of the activity – the implementation phase – the researcher would transfer responsibility to a senior member of staff inside the company. To facilitate this, the researcher would transition into a role as a roadmapping advisor.

Whilst the process continued to be supported by executive management and the purpose (and progress) of the roadmapping process was communicated with key staff, following the transition of the researcher to an advisory role, it was observed that the roadmapping process lost momentum. In particular, this was evident in that a third workshop was not organised or carried out by the company. The issues that manifested in the embedding of the roadmapping process at Tokamak Energy were thus likely to be related to the usefulness of roadmapping and the effect of the handover from the researcher. It is contended both factors relate to the misunderstanding about the purpose of roadmapping.

5.6.1.2. Misinterpretation of the purpose of roadmapping

The roadmapping process should be seen as perpetually unfinished. However, roadmaps can, by contrast, also provide one-time influence during a critical period. Kappel notes that this can be problematic as the perceived usefulness of a roadmap is that it was useful on one occasion alone (Kappel, 2001). If maintained, this can lead to the belief that “roadmaps” are the useful component, rather than the process. This is compounded by the fact that the benefits of the process are often qualitative, e.g. alignment of strategic milestones with TGIs is useful, but the cost savings of the alignment are difficult to measure. If tangible results
can be produced – such as a communications or risk roadmap – then roadmapping is more likely to be considered successful, see (Daim & Oliver, 2008). The focus on what can be described as “roadmaps over roadmapping” was observed during the course of this research. In part, emphasis on developing the communications roadmap for Tokamak Energy may have perpetuated the issue. The communications roadmap was produced to support the resolution of a particular strategic issue, and it was – ostensibly – useful in fulfilling its intended one-time purpose (see 5.5.2.1). If the process developed in this research were to be repeated or redeveloped, the differences between roadmaps and roadmapping – which have been intentionally separated in this thesis, see 3.2.2 – should be emphasised early on to those involved with the activity.

5.6.1.3. Differences between roadmapping and project planning

During this research, it became clear that the differences between roadmapping and traditional project planning (and, by extension, between roadmaps and project plans) were not understood by various staff within the company. Relatedly, the differences are not well characterised in the roadmapping literature. Variations of the question “we already have Gantt charts, how is this different?” were asked by several members of Tokamak Energy staff on several occasions\textsuperscript{154}. The question indicated that many staff saw roadmapping as synonymous with project planning, which already existed within the company and was typically carried out by project managers. The differences between roadmapping and project planning must, therefore, be discussed.

Roadmapping is a form of strategic planning, encompassing strategic thinking. Strategic thinking often involves a not-too-precisely articulated vision of direction. Parts of the roadmapping process are effectively “thinking about planning”, i.e. providing a high-level strategic view that provides clarity on the way forward to enable traditional project planning (Bouhali et al., 2015). Indeed, this is the very purpose of strategic planning. As such, roadmapping is quite different from a project plan, such as a Gantt chart. A Gantt chart displays precisely defined milestones, objectives, and tasks to deliver a specified outcome, and, as long as resources (e.g. a workforce, the required technology and investment) are in place, and if no unexpected obstacles arise, then the project will succeed (European Industrial Research Management Association (EIRMA), 1997). A project plan does not need to be a continuous process. A project plan can be developed, followed, and completed. Of course, it is subject to changes in the plan based on progress or unforeseen circumstances, but typically a project plan is devised under the assumption that there are no unknowns and thus project planning does not account for uncertainty. A roadmap, on

\textsuperscript{154} Refer to footnote 123.
the other hand, presents a view of the desired future in which there are many unknowns, and thus there is inherent uncertainty. Such unknowns could be in the form of unknown competitors, product specifications, physical limits (e.g. in materials), or costs. Moreover, with the knowledge that the future is uncertain, unlike project plans, roadmaps can show a path forward in spite of such unknowns. It instead adopts an approach that supports an agile innovation approach, i.e. not all issues have to be known to progress. Instead, the best possible solution to a problem can be implemented in a project or experiment. If the solution fails, a new solution can be sought. If it succeeds then progress is made. Roadmapping permits imperfect planning, which provides some clarity for detailed project planning to take place on a specific issue identified in a roadmap (e.g. in the context of the application to Tokamak Energy, on a specific sub-TGI). Generally, therefore, project plans and roadmaps have different but complementary functions and are thus best carried out in unison.

This description of the differences in roadmapping and project planning, derived from observation in the industrial application and experience of the researcher at Tokamak Energy, can be used to clarify the role of roadmapping as a method in future applications.

5.6.2. The need for roadmapping software

The roadmap shown in Figure 4-17 was developed using Microsoft Visio. Microsoft Visio has a “layering” function that can be used to show and hide elements of the roadmap. This function was initially intended to be used for the purposes of incorporating and showing linkages between the elements in the roadmap that had been identified in the linkage grids. However, the Microsoft Visio software was found to have significant limitations for active management of the roadmap; the inability to edit content, structure, show linkages, timescales, and – importantly – the lack of capability to link the roadmap to reference external documents. Specifically, there is a large quantity of content beneath the roadmap that cannot be shown. Currently, there is no way to show information contained in linkage grids, TRL assessments, or TGI analysis in the roadmap. Even if the functionality existed, presenting the information in a static format, i.e. printed format, would be chaotic.

In order to maintain, develop and manage the roadmap, dedicated software is required. Various roadmapping software packages have been developed. Firstly, roadmapping software designed specifically to support science and technology roadmapping that was developed by the U.S. Office of Naval Research in the early 2000s was reviewed for suitability ([Zurcher & Kostoff, 1997]). Although the software had several useful features, it was almost two decades out of date and as such was unwieldy, contained bugs, and had limited functionality. Many of the currently available software packages on the market are
geared towards product roadmapping, e.g. Roadmunk, Aha!, and SharpCloud. New software to support the application of roadmap to high-tech start-ups is needed.

5.6.3. Timescales to fusion: Bias in fusion start-ups

Participants in the STIM workshop questioned whether the timescales shown in the Tokamak Energy communications roadmap were biased (5.2.2.5). The question of bias is important. Particularly so because accelerated timescales published by many fusion start-ups are typically in the order of a decade sooner than those suggested possible by public fusion programme. The findings and observations of this research, taking Tokamak Energy as the incumbent example, can provide a perspective on whether timescales are realistic or the subject of marketing bias. However, this is provided in 8.6.1 as a comment of reflection by the researcher.

5.7. Chapter summary

This chapter has evaluated, analysed and discussed the roadmapping method presented in Chapter 4. In particular, the ways in which roadmapping support planning, innovation and communication have been analysed and discussed, with reference to the existing literature and the contributions of this work. As well as several other observations from the application of roadmapping, a workshop with roadmapping practitioners provided insights and ideas to improve the method developed (and process diagrams). Of particular value was the suggestion to introduce a markets layer to better account for commercial drivers.

This chapter addressed research question 2B and provided additional context to address research question 2A, which was addressed principally by the research presented in Chapters 3 and 4. Conclusions to answer research question 2 are collated in Chapter 8.

The next and final chapters of this research will focus on a deep dive into a key issue for the commercialisation of fusion, which is detailed subsequently in 5.7.

5.8. Natural resources: A key challenge to the commercialisation of fusion

A key principle of agile innovation and of the roadmapping process developed in this research is the emphasis on identifying future gaps, both technical and commercial. Many of the identified TGIs for Tokamak Energy are relevant to all fusion development efforts, and all TGIs must be overcome to achieve commercial fusion. This necessitates solutions that are both technically and commercially viable. Many – if not all – of the TGIs are the subject of focused R&D in public fusion programmes as well as in fusion start-ups. However, largely the focus is on the technical issues and not on commercial development, even in ostensibly commercially-focused start-ups. Most efforts are focused on overcoming
the physics TGI to prove the viability of the physics in their concepts (refer once more to the S-T-A-M model in 2.6.2, which shows that fusion is still focused on demonstrating the key scientific step). In other words, whilst start-ups are developing solutions that may lead to successful commercialisation, the majority of effort is placed on overcoming the near-term challenges which are critical to the demonstration of their concepts, e.g. HTS magnets, or other disruptive technologies such as plasma drivers or high-power lasers etc. Naturally, due to restraints on capital and staff, even commercially-focused start-ups are not allocating the same level of emphasis to longer-term challenges. However, the resolution of TGIs should consider the relevant drivers that will ensure that the developed technology will ultimately result in a commercial product.

This thesis has thus far focused on identifying and characterising the challenges to fusion from an engineering systems perspective, with a view of the need to manage the innovation process. A key limitation of this research is that the specific issues that exist within the system have not been explored in depth – even though they are likely to affect that system. Although it is not possible to investigate the plethora of issues that have been identified, in the early stages of the development of TGIs in the roadmapping process, it was determined that there are potential issues surrounding natural resources for deuterium-tritium (D-T) fusion (more specifically, deuterium and tritium as well as the resources required for breeding tritium – see TGI #11 and TGI #12 in Table 4-4). Technologies developed in these areas – perhaps due to the fact that most development has been conducted in publicly funded laboratories operating under a linear model of innovation – has focused on finding solutions that offer the best technical performance. Whilst tritium has been explored as a known problem, the notion that deuterium is abundant has resulted in a lack of exploration into its use as a fuel for commercial fusion.

Similarly, with numerous technical challenges, scientists are focused on developing blankets that are technically functional. Less emphasis on the cost and potential commercial issues. The commercial challenges – in particular the availability, supply and use of several key natural resources – have thus only received limited attention. Such longer-term commercial issues with natural resources, such as the availability of tritium for fusion R&D, and the availability and use of resources for tritium breeding blankets, can have a considerable impact on near-term development. This is particularly true for blanket technology which will likely take a long time to develop due to the high technical complexity. If a blanket design is pursued that is commercially unviable, substantial capital and time may be ill-spent. To avoid locking-in on such pathways that may not lead to commercialisation, an understanding of the commercial issues is required.

Building on existing research, the availability, supply and use of key natural resources are assessed. The findings and insights from the research will provide a commercial
perspective on the issue that can be used to guide future fusion programmes, including Tokamak Energy. The research is split into two chapters. Chapter 6 explores the availability, supply and use of deuterium and tritium as the primary fuels for D-T fusion. Chapter 7 identifies, characterises and assesses critical natural resources required for tritium breeding blankets. The findings and insights from Chapters 6 and 7 are collated in Chapter 8.
Chapter 6. The availability, supply and use of deuterium and tritium

This chapter will, in part, address research question 3. Firstly, the existing literature on the availability, supply, and use of deuterium and tritium is reviewed, from which specific research objectives are outlined. This chapter uses mixed methods: deuterium supply is reviewed via literature-based analysis, and tritium supply is reviewed via a forecast model. Results are presented and discussed in this chapter and collated in Chapter 8 (conclusions).

The content of this chapter can be found in part or whole in the following peer-reviewed publications:

6.1. Deuterium and tritium as fuels for fusion

This section will review the literature on deuterium and tritium as fuels for fusion to reveal the research gaps, and to inform the development of specific research objectives.

6.1.1. Deuterium

Deuterium is a stable isotope of hydrogen and is abundant on earth, and there is an estimated $4 \times 10^{16}$ kg of deuterium in seawater (Wesson & Campbell, 2011). The most common industrial use of deuterium is for heavy water. Heavy water is created when deuterium atoms replace the hydrogen atoms in water, i.e. $\text{H}_2\text{O}$ becomes $\text{D}_2\text{O}$. Heavy water was first produced in Norway in 1934, and soon after became an important part of history for the role it played in the race for the atomic bomb between the Nazis and the allied forces (Waltham, 2002). The demand for heavy water at that time was due to its function as a moderating medium that permits nuclear fission reactions to take place using natural uranium, negating the need for complex uranium enrichment. Following the war, heavy water was used for the same function, but for peaceful and commercial use as a moderator in the Canadian CANDU (CANadian Deuterium Uranium) fission reactor (Miller, 2001).

Heavy water reactors – principally CANDU reactors – have been built around the world, although they are not as widespread as light-water reactors (World Nuclear Association, 2020a). As noted, CANDU reactors use natural uranium which, via the use of heavy water, avoids the cost of uranium enrichment. However, the process of making heavy water is still relatively expensive (Rao, 2011; U.S. Department of Defense, 1998). Heavy water production plants have produced tens of thousands of tonnes of heavy water since the 1940s. Despite the fact that many of these heavy water production plants are no longer in operation, smaller quantities are still produced and are sold at a price of approximately US$ 430 per kg155 (Miller, 2001). The operation of a 1 GWth D-T fusion reactor for one year requires around 30 kg of deuterium, which is expected to be produced by electrolysis of heavy water (Zarnstoff & Goldston, 2017). Therefore, given the quantity of heavy water available, it appears that producing deuterium for fusion is a simple process and not of concern. Indeed, perhaps this provides the rationale as to why few assessments of resources for fusion consider deuterium supply in no more than a few sentences, see (Ward, 2007; Bradshaw, Hamacher & Fischer, 2011; Wesson & Campbell, 2011; Zarnstoff & Goldston, 2017; Rhinehammer & Wittenberg, 1978).

155 2019 dollars converted from 2001 dollars.
6.1.2. Tritium

Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years, via β-decay to produce helium-3 (see equation 6.1) (Galeriu & Melintescu, 2013; Chen, 2011).

\[
\text{Eq. 6.1} \quad ^{3}\text{H} \rightarrow ^{3}\text{He} + \beta^- + \text{anti-neutrino}
\]

Tritium is produced in nature as a decay product of naturally radioactive elements, and by cosmic rays interacting with nitrogen in the atmosphere (Boyer et al., 2009). It does not occur naturally in any significant quantity (Chen, 2011; Ni et al., 2013). However, anthropogenic tritium was produced in large quantities during atmospheric nuclear weapons testing from 1945 to the mid-1960s, where roughly 650 kg of tritium was released into the atmosphere (Galeriu & Melintescu, 2013). While tritium is radioactive; it is not highly ionising. Tritium dissipates quickly in air and cannot penetrate the skin, but it is highly mobile and can readily replace hydrogen. Accordingly, there are health risks associated with the inhalation, skin absorption and ingestion of tritium when in certain chemical forms (Boyer et al., 2009).

Tritium is produced as a by-product of the fission process in CANDU (Canada Deuterium Uranium) reactors through neutron capture in deuterium principally in the heavy water moderator but also in the heavy water heat transfer circuit (PHT), see (Sood, Fong & Woodall, 1997). Tritium can also be intentionally produced via the insertion of TPBARs (Tritium Producing Burnable Absorber Rods) containing lithium-6 into specially designed PWRs. Whilst the production of tritium via TPBARs is specifically for the production of tritium for military purposes (e.g. in the Watts Bar reactor in Tennessee, U.S.), it has previously been supplied to laboratories for other R&D (Bergeron, 2002). Tritium is also produced in small quantities in other types of fission reactors, but typically only in very small quantities (Galeriu & Melintescu, 2013). Figure 6-1 shows the rate of tritium production in the moderator of a typical CANDU reactor; approximately 3.7 Ci/kg per year (which equates to 130 g per year\textsuperscript{156}) until reaching equilibrium when the concentration is at 80 Ci/kg (Bornea et al., 2010; Gerchikov et al., 2015; Sood, Fong & Woodall, 1997; Ni et al., 2013; Galeriu & Melintescu, 2013).

\textsuperscript{156} Tritium is also produced in the primary heat circuit of CANDU reactors but is produced at a rate an order of magnitude lower than in the moderator, see (Sood, Fong & Woodall, 1997).
Tritium in the heavy water moderator in CANDU reactors can be extracted by means of a TRF (Tritium Removal Facility). Only two civilian TRFs exist worldwide: one in Canada (Darlington “DTRF”) and one in South Korea (Wolsong “WTRF”). Although CANDU reactors are capable of producing up to 130 grams per year and the total capacity of both TRFs combined is 3.27 kg of tritium per year, the total recovery rate is between 1.5 and 1.7 kg per year (Ni et al., 2013). Romania plans to commission a TRF to detritiate its two longstanding CANDU reactors at Cernavoda Nuclear Power Plant, which could provide an important third tritium supply source. Tritium extracted from CANDU via the TRFs is stored until it either decays to helium-3 or is sold. Currently, accounting for all existing TRF supply, the global inventory of tritium is estimated at 30 kg (Ni et al., 2013; Willms, 2008).

As the tritium required for a 1 GW thermal power station is 55.6 kg per year, significantly larger quantities of tritium will be required for a commercial fusion programme. As introduced in 1.2.3, D-T fusion reactors are expected to breed tritium to become self-sufficient. Theoretically, tritium breeding is possible, and there are several ongoing programmes to develop the technology, but tritium breeding blankets have not yet been tested beyond lab-scale (see 7.1.2). In the near-term, however, externally-sourced tritium from CANDU is essential for fusion R&D as well as for the start-up of future commercial reactors\textsuperscript{157}. ITER will test proof-of-concept tritium breeding blankets but will not breed

\textsuperscript{157} There are potential routes to D-T fusion without a start-up quantity of tritium, which is discussed in 6.3.6.5.
tritium and thus will require roughly 18 kg of CANDU tritium over its planned 20-year operation (Glugla et al., 2007). ITER will thus be a very large net consumer of tritium, whilst not fully demonstrating tritium breeding technology. A next-step fusion device will still require an external supply of tritium yet the supply from CANDU reactors uncertain. Whilst it is possible that new CANDU reactors will be built and some existing reactors may be granted life extension, several CANDU reactors are close to – or are already – being decommissioned.

6.1.3. Problem statement and research approach

6.1.3.1. Problem statement: Deuterium

Whilst deuterium is abundant and production ample, the physical supply of deuterium and the implications of using deuterium for fusion have not been considered in the literature. It is hypothesised that there are factors relating to the supply chain capability, as well as issues relating to the export control and risk of indirect proliferation that have not been characterised. To the best of the researcher’s knowledge, the analysis in 6.2 is the first comprehensive analysis of deuterium supply and use.

6.1.3.2. Problem statement: Tritium

Fusion R&D efforts are expected to generate significant demand for externally sourced tritium in the coming years. The tritium requirement of the – now delayed – ITER tokamak will place strain on the global tritium inventory. Further tritium demand may also come from a number of the private sector fusion start-ups that have emerged in recent years (see Chapter 2) and also public programmes unconnected to ITER such as the South Korean K-DEMO and the Chinese Fusion Experimental Test Reactor (CFETR) projects.\(^{158}\) Potential competition for tritium may cause complications for the operation of ITER and may also put next-step devices in jeopardy. Due to the uniqueness of tritium supply, and in particular, with the changes in the potential demand for tritium owing to the delay of ITER and the emergence of start-ups, previous assessments of the tritium supply and demand forecast must be reviewed and updated using recent information. 6.3 details a forecast model to compare tritium supply against future fusion demand.

\(^{158}\) Unlike ITER, both K-DEMO and CFETR are expecting to demonstrate tritium self-sufficiency by incorporating breeding blankets into the reactor design.
6.1.3.3. **Secondary research questions**

In this research, in addition to the primary research question (research question 3), two secondary research questions are defined to guide the research. Each question applies to both deuterium and tritium:

- What are the issues with the supply of the resource for fusion?
- Are there differences in resource supply between public programmes (generally pursuing larger machines) and fusion start-ups (generally pursuing smaller machines)?

### 6.2. Deuterium supply

#### 6.2.1. Heavy water production

Table 6-1 shows the locations of several notable past and current heavy water plants.

<table>
<thead>
<tr>
<th>Production Year</th>
<th>Country</th>
<th>Plant name/Location</th>
<th>Process</th>
<th>Capacity Tonnnes per year</th>
<th>Current Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1934-unknown</td>
<td>Norway</td>
<td>Rjukan</td>
<td>Electrolysis/ H\textsubscript{2}O-H\textsubscript{2} exchange</td>
<td>12</td>
<td>unknown</td>
</tr>
<tr>
<td>1952-96</td>
<td>United States</td>
<td>Savannah River</td>
<td>GS</td>
<td>500</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>1971-85</td>
<td>Canada</td>
<td>Port Hawkesbury</td>
<td>GS</td>
<td>400</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>Did not operate</td>
<td>Canada</td>
<td>Bruce D</td>
<td>GS</td>
<td>700</td>
<td>Dismantled</td>
</tr>
<tr>
<td>Did not operate</td>
<td>Canada</td>
<td>LaPrade</td>
<td>GS</td>
<td>720</td>
<td>Dismantled</td>
</tr>
<tr>
<td>1979-97</td>
<td>Canada</td>
<td>Bruce A</td>
<td>GS</td>
<td>800</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>1976-85</td>
<td>Canada</td>
<td>Glace Bay</td>
<td>GS</td>
<td>400</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>1981-97</td>
<td>Canada</td>
<td>Bruce B</td>
<td>GS</td>
<td>800</td>
<td>Decommissioned</td>
</tr>
<tr>
<td>1988-</td>
<td>Romania</td>
<td>Drobeta-Turnu Severin</td>
<td>GS</td>
<td>270</td>
<td>Operating</td>
</tr>
<tr>
<td>Did not operate</td>
<td>Roman Sulphide process\textsuperscript{159}</td>
<td>Monothermal Ammonia-Hydrogen (NH\textsubscript{3}-H\textsubscript{2}) isotopic exchange</td>
<td>100</td>
<td>Operating</td>
<td></td>
</tr>
<tr>
<td>2006-</td>
<td>Iran</td>
<td>Arak</td>
<td>GS</td>
<td>8</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

\textsuperscript{159} Information provided courtesy of Stephen Strikwerda of Kinectrics Inc., Canada.
The majority of heavy water is produced by the Girdler Sulphide process and primarily is sourced from Canada (Miller, 2001; Waltham, 2002). However, Indian heavy water production is dominated by the ammonia-hydrogen exchange process. India is estimated to have the capacity to produce around 500 tonnes per year for its own heavy water reactor fleet see (Rao, 2011). However, the country’s status as a non-signatory of the nuclear non-proliferation treaty (NPT) means that heavy water could be diverted to breed plutonium and tritium for a nuclear weapons programme\textsuperscript{160}. Relatedly, Iran operates a small heavy water production facility at its Arak nuclear facility, which was previously controlled as a condition of the JCPOA (Joint Comprehensive Plan Of Action), colloquially known as the “Iran Nuclear Deal”. However, since the U.S. pulled out of the agreement, the Arak reactor has become a cause for concern (Borger, 2020). Chinese heavy water production is unknown, but two new heavy water reactors are planned in partnership with the Canadian company SNC-Lavalin (see (SNC Lavalin, 2019)).

Around 1980, four Canadian heavy water plants were producing over 2,000 tonnes per year, but all were decommissioned by 1997 due to the lack of demand (Miller, 2001). However, all Canadian heavy water, if reprocessed and tritium removed via the DTRF, can be reused. As such, although heavy water is used in CANDU reactors, it is considered a recyclable commodity. Despite limited current production, Ontario Power Generation (OPG)\textsuperscript{161} has produced – and still owns – at least 7,400 tonnes of heavy water (Ontario Power Generation, 2019). Moreover, given that no new CANDU\textsuperscript{162} reactors are planned – with the exception of the two Chinese advanced CANDU reactors – and several existing CANDU reactors due to be shut down, e.g. six reactors at Pickering are due for shutdown in 2024 (see (World Nuclear Association, 2020a)), it is likely there will be a surplus of heavy water available. Existing heavy water that is surplus to requirements is sold by OPG to customers such as Isowater; a company focused on developing deuterium products (see (Isowater, n.d.)). Finally, in addition to the existing heavy water inventories, Canada now only produces small amounts of new heavy water through the operation of an advanced CECE (Combined Electrolysis and Catalytic Exchange) plant at Chalk River National Laboratory, Canada. The CECE plant is primarily focused on the separation of hydrogen and deuterium but can also be used to produce heavy water at approximately 50 tonnes per year (Miller, 2001; Personal communication with Stephen Strikwerda, Kinectrics Inc. Canada, 2019).

\textsuperscript{160} Heavy water and proliferation are discussed in 6.2.5.

\textsuperscript{161} OPG is owned and operated by the Canadian government.

\textsuperscript{162} China has plans for heavy water moderated thorium reactors or advanced CANDU which may drive heavy water production, see (World Nuclear Association, 2020b).
6.2.2. Deuterium production for fusion

Understanding heavy water production capability is important, as it shows that although the supply chain for new heavy water production is limited, existing heavy water to be converted into deuterium is ample for the purposes of fusion. Deuterium can be produced from heavy water through various processes but is most commonly produced via electrolysis. To yield 1 kg of deuterium from heavy water via electrolysis requires 5 kg of D₂O (calculated by noting that deuterium in D₂O makes up 20% of the total mass). As such, the required supply of deuterium for fusion – 30 kg per GWth per year – does not appear problematic given the thousands of tonnes of heavy water in Canada alone. Deuterium required for fusion R&D in the near-term is already available in sufficient quantities from sellers such as BOC and Isowater (BOC (Linde Group), n.d.; Isowater, n.d.). However, the long-term supply of deuterium for a commercial fusion industry must be considered.

The following calculation estimates the quantity of deuterium required for the first one hundred commercial fusion reactors, i.e. the industrial scale-up phase:

To account for isotope recycling and deuterium retention in materials of a fusion reactor\(^{163}\), it is assumed that the requirement of a fusion reactor is for 50 kg deuterium per GWth per year. Hence, the first hundred 1 GWth fusion power plants would require 5,000 kg (5 tonnes) of deuterium per year, which corresponds to 25 tonnes of heavy water. Over a 40 year lifetime, assuming only one fusion hundred plants are built, 200 tonnes of deuterium would be required, meaning that 1,000 tonnes of heavy water are needed. The current stockpile in Canada – 14,500 tonnes – could, therefore, supply around 1,450 fusion reactors. Moreover, the capacity of the existing Canadian CECE plant could supply enough deuterium to sustain 200 GWth installed fusion reactors.

Whilst existing supply chain capacity appears ample; in reality, it is more likely that a dedicated heavy water and deuterium production facility to support the fusion industry would be commissioned. Candidates for future production of deuterium for fusion are either the CECE process or the CIRCE (Combined Industrial Reforming and Catalytic Exchange) process. The CIRCE process can be used to produce deuterium from steam methane reforming, which could be used to simultaneously produce hydrogen for future hydrogen industry and deuterium for the fusion industry (Miller, 2001).

\(^{163}\) See (Sawan & Abdou, 2006).
6.2.3. Cost of deuterium for fusion

The cost of electrolysis to produce deuterium gas must be estimated. As noted, 5 kg of D2O is required to produce 1 kg of D2. It costs around US$ 650\textsuperscript{164} to produce 1 kg of heavy water (Miller, 2001). The cost of standard hydrogen electrolysis is in the region of US$ 1 to 10 per kg of hydrogen (Acar & Dincer, 2014). Assuming the same cost for deuterium electrolysis, the cost to produce 1 kg of deuterium is thus estimated to be in the region of US$ 2,250 per kg; higher than the US$ 1,000 per kg cited in the literature (Tanabe, 2009; Bradshaw, Hamacher & Fischer, 2011). Despite this calculation, deuterium at its current market price may provide a truer reflection of the cost as other parts of the supply chain rather than just production are accounted for. The price of heavy water and deuterium depends on the grade. Higher purity is – naturally – more costly. For 99.96% isotopically pure deuterium (in the form of D\textsubscript{2} gas), Sigma Aldrich quotes 10 litres at US$ 275\textsuperscript{165} (Sigma Aldrich, 2020). Given that 1 litre of gas (at STP) contains 0.16659 grams of deuterium, the cost of deuterium is therefore approximately US$ 165,000 per kilogram. This is significantly higher than US$ 1,000 per kilogram and – due to the purity required – may reflect a truer cost of deuterium for fusion. However, given deuterium in the order of tens of kilograms will be required for fusion R&D, the cost is still negligible particularly compared with tritium which is sold at an artificial price of around US$ 30 M per kg (Ni et al., 2013). Nevertheless, it is instructive to calculate the cost of the first hundred fusion reactors based on both cost scenarios, i.e. deuterium at US$ 2,250 per kg and at US$ 165,000 per kg, as shown in Table 6-2.

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Deuterium cost per year (US$ 2,250/kg)</th>
<th>Deuterium cost per year (US$ 165,000/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (50 kg D\textsubscript{2})</td>
<td>US$ 112,500</td>
<td>US$ 8.25 M</td>
</tr>
<tr>
<td>100 (5000 kg D\textsubscript{2})</td>
<td>US$ 11.3 M</td>
<td>US$ 825 M</td>
</tr>
</tbody>
</table>

Table 6-2   Annual deuterium costs for commercial fusion reactors based on low and high estimates of deuterium price

The total cost using the higher price of deuterium could be US$ 8.25 M per reactor per year. However, this cost must be put into context. Simply, if a 1 GWth fusion reactor produces electricity at approximately 40% efficiency with no downtime, it will supply around 3,500 GWh of electricity in one year. If sold at the U.S. spot market electricity price of US$ 43.42

\textsuperscript{164} Converted from 2001 $US to 2019 US$.

\textsuperscript{165} Converted from GBP based on exchange rate December 2019.
per MWh (average wholesale price for December 2019, see (U.S. Energy Information Administration, n.d.)), the fusion power plant would generate revenue of US$ 152 M. Deuterium fuel would thus constitute roughly 5% of revenue (at US$ 165,000 per kg). In the fusion literature, deuterium fuel is commonly cited as being negligible (see (Ward, 2007; Tokimatsu et al., 2003)). For the same conditions, deuterium at US$ 2,250 per kg constitutes only 0.07% of revenue, which could indeed be considered negligible. However, whilst the real cost is largely uncertain, the incumbent analysis indicates that deuterium is a cost that must be considered and better understood.

6.2.3.1. Capital costs of deuterium production for fusion

It is unlikely that the fusion industry would have to fund deuterium plants in the near-term, at least, due to existing capacity to supply heavy water and deuterium. It is even feasible to suggest that the tritiated heavy water owned by OPG from incumbent CANDU reactors could be sold directly to the fusion industry. Tritiated heavy water contains both the fuels required for a fusion reactor which could be extracted using specially designed isotope separation systems at fusion reactor sites. However, in the longer-term, dedicated production plants may be required to produce deuterium specifically for fusion. It can be estimated that an 800 tonne per year heavy water production plant, which would yield 160 tonnes of deuterium, would be sufficient to support approximately 3,000 1 GWth fusion reactors. If operating a production plant based on the Girdler Sulphide exchange process producing 800 tonnes of heavy water per year, the cost would be approximately US$ 600 M\textsuperscript{166}.

6.2.4. Environmental costs of deuterium production

Heavy water production is an energy-intensive process and typically uses fossil fuels to generate the temperatures required, thus producing carbon emissions (Miller, 2001; Agarwal, 2016; Rao, 2011)\textsuperscript{167}. Energy requirements for both the ammonia-hydrogen exchange process and the G-S process are in the region of 30 GJ per kg of heavy water produced (two-thirds of the energy for process heat and one third for electricity) (Agarwal, 2016; Rao, 2011). If the process heat were generated by natural gas, and if considering a 50 kg CO\textsubscript{2} is produced per GJ (Hultman et al., 2011), then the carbon emissions equal 1

\textsuperscript{166} Cost extrapolated from the cost of Bruce Heavy Water plant accounting for inflation and a 10% additional cost for increased safety standards, from (Atomic Energy of Canada Ltd (AECL Canada), 1991).

\textsuperscript{167} For example, Romania’s heavy water production plant burnt lignite to produce steam for the process.
tonne of CO$_2$ per kg of heavy water. Additional carbon costs would need to be considered for the 154,000 kg of feed water required to produce 1 kg of heavy water (U.S. Department of Defense, 1998), and also for the electricity (which could come from clean sources, e.g. nuclear fission). Whilst potentially small, there is also a carbon footprint associated with the build and standard operation of the heavy water or deuterium production plant, and the deuterium transport supply chain.

Any concerns over the potential environmental impact of removing large quantities of deuterium from seawater are realised to be trivial when noting that the Pacific Ocean alone contains 710 million km$^3$ of water, which is enough to produce 55 trillion m$^3$ of heavy water!

Such estimates here are intended to provide a first approximation, and they usefully provide an indication that the cost of deuterium may not be negligible. In the longer-term, carbon costs could be negated entirely as deuterium production for fusion could be powered by fusion energy reactors in-situ, e.g. by breeding deuterium by bombarding hydrogen atoms in a blanket, as suggested in (Arias & Parks, 2015).

6.2.5. Export control, regulation and proliferation concerns

Both heavy water and deuterium are subject to export control, per (British Government, 2012; International Atomic Energy Agency (IAEA), 2019; Canadian Nuclear Safety Commission, 2000)$^{168}$. Specifically, the control applies to deuterium, heavy water, and other deuterium compounds containing deuterium in a concentration of over 1:5000 hydrogen atoms. Furthermore, equipment for the production or concentration of heavy water, deuterium and deuterium compounds is also subject to export control, see (Canadian Nuclear Safety Commission, 2000; British Government, 2012). The primary reason for the export control of deuterium and deuterium technologies relates to non-proliferation. Therefore, it is likely that the existing framework for the control of heavy water and deuterium will apply to fusion, i.e. controls, regulation and export licenses for international deuterium supply. Export of certain technologies to certain nations not a party to the NPT, for example, or those that are on export control blacklists, for fusion this may not be possible. If an unstable nation or clandestine group were to be supplied with deuterium producing technology, then it has one of two paths to proliferation:

1. Any country seeking large quantities of heavy water is potentially using it to moderate a fission reactor to produce plutonium, and thus heavy water presents a route to proliferation. A nation possessing a heavy water reactor – such as Iran – has the means to produce fissile material using natural non-enriched uranium.

$^{168}$ Also refer to the restrictions on heavy water production and supply in the JCPOA treaty.
Hence, heavy water presents a route to proliferation as it allows that nation to bypass uranium enrichment and related technological infrastructure (U.S. Department of Defense, 1998).

2. The second route involves the use of deuterium, alongside lithium-6 (which is explored in Chapter 7), being combined to produce lithium deuteride, Li\textsuperscript{6}D – the critical material for a thermonuclear weapon (U.S. Department of Defense, 1998).

Ipso facto, the fusion supply chain has the potential to be diverted for proliferation. Whilst the quantities of materials required for fusion are small, even for a fleet of fusion reactors, it is the capability that, e.g. heavy water production technology brings with it that presents a proliferation risk. Therefore, the supply of deuterium represents a potential issue to the commercialisation of fusion, and thus the incumbent analysis challenges the notion that fusion could be deployed ubiquitously. The stringency of the existing licensing and export control may cause the global rollout of fusion technology to be stymied if the issue is not addressed in the early stages of fusion development. Thus far, studies on the proliferation potential of fusion do not consider deuterium\textsuperscript{169}, see (Englert, Balloni & Liebert, 2010; Glaser & Goldston, 2012).

In summary, challenges deuterium supply and use in relation to export controls and non-proliferation may limit fusion’s market to “safe” nations, i.e. those party to the NPT, and thus it may limit its claim to be a ubiquitous, safe energy source; commonly cited as a key benefit of the technology. Whilst a prescient issue, however, it is not an insurmountable one. The fusion industry should liaise with governments and government regulators, well as the IAEA, to more comprehensively understand challenges associated with deuterium. One potential resolution could be to raise the restrictions on the maximum supply of deuterium; a 200 kg cap is placed on the international trade of deuterium (British Government, 2012; Canadian Nuclear Safety Commission, 2000). This could facilitate the direct supply of deuterium rather than the technology to produce it. Such stringent controls would prohibit certain countries from being able to manage their own fusion supply chain and will instead be dependent upon other nations for deuterium fuel, which represents a geopolitical issue and limits energy security and security of supply for any nation using a fusion reactor. However, it might provide a solution to allow the global deployment of fusion.

\textsuperscript{169} Both reviews are focused on direct proliferation (clandestine production, covert production and breakout), rather than what is here detailed as an indirect route to proliferation.
6.2.6. Conclusions

To the best of the researcher’s knowledge, the issues detailed in this section have not previously been analysed or discussed. Deuterium is widely abundant and likely to be available for fusion experiments and for a commercial programme from the resource perspective. The cost of deuterium is also determined as potentially significant, which challenges existing understanding. The principal concern over the use of deuterium in fusion relates to export control, and that deuterium production capability may provide an indirect route to proliferation. Two routes ahead are possible for fusion. Either individual nations develop their own deuterium supply and submit to having IAEA safeguarding and monitoring of production, or the controls of the supply of deuterium (but not heavy water) revised.

Finally, from the perspective of deuterium availability and supply, it can be concluded there is no distinction between public fusion programmes using larger quantities of deuterium, and smaller prototypes by fusion start-ups. Whilst the cost may be lower for fusion start-ups requiring less resource; which further supports the notion that fusion start-ups attempting to go fast by keeping costs low and designs simple, greater speed and lower cost may be negated by the fact that public programmes, operating at national laboratory sites, may find it easier to conform with the regulations surrounding heavy water or deuterium supply and use. The aforementioned issues relating to regulation, however, are an issue for all fusion efforts that should be solved jointly.

6.3. Tritium supply for fusion

Due to its scarcity on Earth and due to its limited production as a by-product of CANDU reactors, tritium supply represents a unique issue. This section details a model to forecast the supply of tritium, compared against the expected demand from fusion, specifically ITER and fusion start-ups.

6.3.1. Model Description: Overview and scenarios

The model forecasts tritium availability using data collated from sources estimating both the supply and demand of tritium. The forward time horizon is 40 years, but also includes a 10-year history from 2007 coinciding with the start of tritium production in South Korea. The model builds upon estimates in (Willms, 2008; Ni et al., 2013; Kovari, 2016), adopting alternative methods and using new data to give an updated view. In particular, the model considers key changes in the future supply and demand landscape:

- On the supply side, the high-level operational decisions regarding future Canadian CANDU refurbishment, the political decision to phase out nuclear power in South
Korea, and the potential impact of Romanian tritium\textsuperscript{170} (Independent Electricity System Operator (IESO) Canada, 2015; Canadian Nuclear Association, 2017; Rothwell, 2017).

- On the demand side, the delay to ITER is considered, as well as the tritium needs of alternative fusion approaches, including private-sector start-ups and other domestic projects.

Together these factors may limit the quantity of tritium available on which to launch a commercial fusion programme. Accordingly, the model considers two supply scenarios (further detailed in 6.3.2)

\begin{itemize}
  \item \textbf{Supply scenario 1}: Canadian Production to end of life of DTRF (2055)\textsuperscript{172}, South Korean production until 2032 in WTRF (whereby South Korean CANDU reactors cease operation by 2030), zero Romanian production (Romanian TRF is not built).
  \item \textbf{Supply scenario 2}: Canadian Production to end of life of DTRF (2055\textsuperscript{1}), South Korean production in WTRF until the end of the model time horizon, Romanian production from 2024 until the end of the model time horizon (Romanian TRF is commissioned).
\end{itemize}

Which are compared against two demand scenarios (further detailed in 6.3.3):

\begin{itemize}
  \item \textbf{Demand scenario A}: ITER demand only, first tritium for tritium system commissioning starting in 2027, and full D-T operation starting 2035.
  \item \textbf{Demand scenario B}: Enhanced demand scenario. Demand from private-sector fusion start-ups, as well as independent government fusion projects, in addition to ITER demand as with demand scenario A.
\end{itemize}

\subsection*{6.3.2. Tritium supply}

The following general assumptions are made:

- Historical data is extrapolated to build projections based on real-world data.

\textsuperscript{170} Romanian tritium was explored as a separate case study, detailed in 6.3.2.3 and published by the PhD researcher in (Pearson \textit{et al.}, 2017).

\textsuperscript{171} The two supply scenarios reflect lower and upper bounds of tritium production respectively. At the current time, the uncertainty surrounding both the future of the South Korean nuclear power programme and the Romanian TRF suggests that supply scenario 1 is the most likely trajectory.

\textsuperscript{172} Existing TRFs require life extension and thus Canadian DTRF undergoes life extension.
- It is assumed that all CANDU reactors operate at the same capacity factor and that tritium production is directly proportional to the rated power output. The outage schedule for Canada’s Darlington TRF (DTRF) details that servicing creates outages on a three-year cycle, with six months outage in year one, three months outage in year two, and zero months outage in year three, per the schedule, outlined in (Ontario Power Generation, 2007). This schedule is assumed to apply for all TRFs and reflects real-world operation. Therefore, reactor outages, planned or unplanned (including refurbishment), are not considered to affect the rate of tritium supply.
- It is assumed that no additional CANDU reactors will be built anywhere in the world.
- Although, for instance, ITER may have its tritium needs wholly provided by Canada\textsuperscript{173}, the model assumes that tritium that is supplied from a virtual stockpile compiling tritium from all TRFs.

Finally, at the start of the time horizon in the model (2007), the WTRF begins operation. Until this time, therefore, Canada’s DTRF is the world’s only tritium supplier. The quantity of tritium in DTRF is thus estimated from historical data as being approximately 21.1 kg in 2006\textsuperscript{174} (Fong, 2012), aligned with previous estimates in (Willms, 2008).

6.3.2.1. Canadian tritium supply

Historical data from DTRF was used to calculate average production in Canada. Total production from the start of DTRF operation in 1989 to 2011 was 42.5 kg (409 MCi)\textsuperscript{175}, which is assumed to be at an average rate of 1932 g/year (18.6 MCi/year) (Fong, 2012). The tritium production rate is considered to be proportional to the total power output of all online CANDU units in any given year, i.e. 1932 g (18.6 MCi) is the maximum annual quantity of tritium that is produced in DTRF when all CANDU units are online and operating. Projections for refurbishment are taken from (Independent Electricity System Operator (IESO) Canada, 2015; World Nuclear Association, 2020a; Canadian Nuclear Association, 2017) and used to determine the proportion of reactors in operation for each year in the model time horizon, as shown in Figure 6-2 and Figure 6-3.

\textsuperscript{173} per an in-principle contract for tritium delivery described in (Glugla \textit{et al.}, 2007), which may now be ineffective due to delays to ITER.

\textsuperscript{174} Accounts for non-fusion demand of 0.2 kg/year from the start of the DTRF.

\textsuperscript{175} Tritium quantities for TRF production in this section are given in grams and Curies, as the literature uses both units. For the remainder of this thesis, tritium quantities are measured in grams only, where the conversion is 9620 Curies to 1 gram (see 6.3.2.3.2).
Refurbishment of DTRF is scheduled for 2025 but is assumed to remain online during refurbishment with no long-term outage. It is therefore assumed that the production of tritium is unaffected. Refurbishment extends the life of DTRF by 30 years, so it is assumed to shut down in 2055. Although DTRF continues to operate, production of tritium still decreases over time in line with the steady shutdown of the Canadian CANDU fleet, per estimated schedules in (Canadian Nuclear Association, 2017; World Nuclear Association, 2020a). Finally, given that detailed plans regarding the future of Canadian CANDU have been published, only one scenario is modelled for tritium production from DTRF. The generation rate and inventory of tritium from DTRF for the model are shown in Figure 6-4.

Figure 6-2 Refurbishment schedule for Canadian CANDU reactors (Darlington and Bruce), reproduced with permission from (Canadian Nuclear Association, 2017).

Figure 6-3 Refurbishment schedule for Canadian CANDU reactors (Bruce Power), reproduced with permission from (Independent Electricity System Operator (IESO) Canada, 2015). Copyright © 2001-2020 Independent Electricity System Operator, all rights reserved. This information is subject to the Terms of Use set out in the IESO’s website (www.ieso.ca).

Data shown were deemed to supersede those in Figure 6-2 where schedules conflicted.
6.3.2.2. South Korean tritium supply

Historical data from the Wolsong TRF (WTRF) was used to estimate average tritium production as 780 g/year (7.5 Mci/year) (Han, 2013). As with DTRF, tritium production from WTRF is assumed to be proportional to the number of CANDU units online, i.e. 780 g (7.5 Mci/year) is the maximum annual quantity of tritium produced in WTRF when all CANDU units are online and operating. Two supply scenarios were modelled for the South Korean case due to the uncertainty:

- In supply scenario 1, the WTRF is assumed to shut down in line with the phasing out of nuclear power in South Korea in line with current political decisions. CANDU reactors at Wolsong will run until the end of their current license, with national nuclear power generation steadily declining from 2022 through 2030. Thereafter, residual heavy water from the final reactor shutdown is processed at a reduced rate until the WTRF is shut down in 2032.

- In supply scenario 2, South Korea is instead assumed to continue dependence on nuclear power. In this scenario, the already refurbished Wolsong unit 1 will shut down in 2038, Wolsong CANDU units 2 to 4 will be refurbished in series between 2022 to 2030, allowing operation for a further 30 years. As with the DTRF, the WTRF is assumed to undergo online refurbishment before the end of its design lifetime in 2047 and thus will continue servicing the refurbished CANDU reactors at Wolsong. In supply scenario 2, it is assumed that tritium production from South Korea will continue beyond the end of the model time horizon.

The generation rate and inventory for both scenarios at WTRF are shown in Figure 6-5.
6.3.2.3. Romanian tritium supply: A case study

Separate research was carried out to forecast Romanian tritium production to feed into the global tritium supply model. A different, dedicated approach is required for the Romanian tritium case, as – unlike Canada and South Korea – the Romanian TRF is not yet built. The specific method and results are presented here in the context of the contribution to the global supply model177.

6.3.2.3.1. The potential supply of Romanian tritium

Around 20% of electrical energy in Romania is provided by two CANDU units at the Cernavoda nuclear power plant. Unit 1 is nearing the end of its original design lifetime and must be refurbished to extend its operation, see (Societatea nationala Nuclearelectrica, 2015). Unit 2 has been operating since 2007 and will be refurbished in the 2030s. Although originally the TRF for Cernavoda (CTRF) was planned for the mid-2010s, the design is currently under review by Romania’s nuclear regulator having been finalised in 2015 after additional safety measures were considered following the Fukushima accident in Japan, 2011 (Societatea nationala Nuclearelectrica, 2015; Stefan et al., 2017). The decision for Romania to proceed with the CTRF is predicated on the consideration of safety and reactor performance. However, Romania has an opportunity to produce tritium to become a key

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177 Additional analysis on Romanian tritium can be found in the following peer-reviewed publication published by the PhD researcher (Pearson et al., 2017).
global tritium supplier and the only tritium supplier in the European Union. In particular, based on the current schedule, CTRF will be commissioned by 2024 coinciding with the refurbishment of Cernavoda unit 1 (subject to delays, see (Stefan et al., 2017)). Coincidentally, this aligns favourably with the operation of ITER.

6.3.2.3.2. Estimating Romanian tritium production

In 2011, the tritium concentration in the heavy water moderator of Cernavoda units 1 and 2 was 54 Ci/kg and 20 Ci/kg, respectively. Figure 6-6 shows the concentration in unit 1 to 2013. Accounting for an increase in tritium concentration of 3.7 Ci/kg per year, the tritium concentration is expected to have reached equilibrium at 80 Ci/kg in unit 1 by the start of CTRF operation (2024) (Bornea et al., 2010; Gerchikov et al., 2015; Sood, Fong & Woodall, 1997).

[FIGURE REDACTED FOR COPYRIGHT REASONS]

Figure 6-6 Tritium content in Cernavoda Unit 1 1998 to 2013, in Ci/kg (no newer data have been published), from (Gerchikov et al., 2015).

CTRF is designed to reduce and maintain tritium concentration in the heavy water moderator in both reactor units to a concentration of 10 Ci/kg (Bornea et al., 2010; Zamfirache et al., 2009). However, due to the total volume of moderator and coolant in each CANDU unit and CTRF processing capacity, approximately two years is required to reduce the initial concentration to 10 Ci/kg in each unit. Thereafter tritium concentration will be maintained below 10 Ci/kg by alternating between Cernavoda Units 1 and 2 on a

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178 One CANDU unit has an inventory of 530 tonnes of heavy water: 200 tonnes for the PHT; 270 tonnes for the moderator; and 60 tonnes for loss make-up (Gerchikov et al., 2015).

179 It is assumed that the CTRF will run for 6500 hours per year, processing 40 kg heavy water per hour, meaning a total of 265,000 kg heavy water is processed per year, per (Zamfirache et al., 2010).
one-year cycle,\textsuperscript{180} meaning highest tritium yield is expected during the first four years of operation of the CTRF. Accordingly, Unit 1 will begin detritiation in 2024 and finish in 2026. As noted, Unit 1 is expected to undergo refurbishment for life extension over a two-year period coinciding with detritiation starting 2024\textsuperscript{181}. Unit 2 will start detritiation following the completion of Unit 1 in 2026. By the start of its detritiation cycle in 2026, the concentration of tritium in the moderator of Unit 2 is expected to have reached 72 Ci/kg. Refurbishment of Unit 2 is expected a decade later in 2035. Figure 6-7 shows the concentration of tritium in Units 1 and 2 over the lifetime of CTRF.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{tritium_concentration_graph.png}
\caption{Tritium concentration in the moderator of Cernavoda Unit 1 and Unit 2 during detritiation in Cernavoda TRF (CTRF).}
\end{figure}

The tritium extraction data, shown in Figure 6-7, was used to determine the mass quantity of tritium extracted each year. Curies per kg must be converted into grams of tritium. The following calculation was used (based on information in (Sood, Fong & Woodall, 1997; Son, Lee & Kim, 2009; Galeri & Melintescu, 2013)):

\begin{itemize}
\item Ci/kg in heavy water is multiplied by the number of kilograms processed by CTRF per year (265,000 kg, per footnote 179) to give the total number of curies per year.
\end{itemize}

\textsuperscript{180} Tritium concentration in the PHT reaches a maximum of 2-3 Ci/kg, but for this model it is assumed to be zero. Despite this, it is assumed that all 530 tonnes of the heavy water inventory will pass through the CTRF, hence the increased detritiation cycle time.

\textsuperscript{181} It is assumed that unit 1 will undergo a two-year detritiation cycle of its heavy water whilst in an offline state during refurbishment (Gerchikov et al., 2015).
Curies are converted to becquerels by multiplying by $3.7 \times 10^{10}$ (Ci to Bq conversion factor, per (Allisy, 1995)).

Becquerels are divided by the decay constant for tritium to give the number of atoms, calculated from $T_{1/2} = 0.693 \cdot \lambda$ (where $T_{1/2}$ for tritium is 12.3 years).

The number of moles can then be calculated by dividing the number of atoms by Avogadro’s constant ($6.022 \times 10^{23}$).

From the number of moles, the mass ($M$) can be determined by multiplying the number of moles by the atomic mass ($M_a$) of tritium ($M_a = 3.016$).

Thus, a tritium-specific curie to grams conversion factor can be derived: one gram of tritium is equivalent to roughly 9620 curies (see footnote 175).

### 6.3.2.3.3. Results

The graph in Figure 6-8 shows tritium inventory over 30-year operation of the CTRF starting 2024 (accounting for tritium decay at 5.47% per year).

![Figure 6-8](image)

**Figure 6-8** Forecast of tritium in CTRF 2024 to 2054.

The tritium recovered over the first four years of operation generates a base inventory of roughly 4 kg. The inventory remains in a near-constant state at 4 kg until a slight decline is caused by refurbishment and resulting offline state of unit 2182.

### 6.3.2.3.4. Contribution of Romania to the global supply model

In supply scenario 1, Romania’s Cernavoda TRF (CTRF) is never built, so Romanian tritium is zero. In supply scenario 2, the CTRF will be commissioned in 2024 with a 40-year design

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182 It is assumed that unit 1 does not undergo a two-year cycle during unit 2 refurbishment, and isotope production is set to zero for the year 2037.
lifetime, as detailed. CTRF will operate until the end of the model time horizon. The generation rate and inventory for scenario 2 at CTRF are shown in Figure 6-9 in the context of the global tritium supply model.

![Figure 6-9](image)

**Figure 6-9** Forecast of tritium production in Cernavoda (CTRF) for supply scenario 2 only (Romanian tritium production in scenario 1 is zero).

### 6.3.2.4. Non-CANDU supply of tritium and exclusions

The model excludes non-CANDU sources. However, two potential sources of tritium were considered. India has the capability to produce tritium from its fleet of heavy water reactors\(^\text{183}\), but a TRF has not been considered for the development of tritium for commercial purposes. As noted in the context of heavy water supply (6.2.5), India is a non-signatory to the nuclear NPT, and as such not all reactors are operated under international safeguards (U.S. Department of Defense, 1998; World Nuclear Association, 2020c). Ergo, tritium produced from its heavy water reactors by an Indian could be diverted for non-peaceful purposes\(^\text{184}\). In consequence, Indian tritium was excluded from consideration in the model\(^\text{185}\). Tritium production from light water fission reactors was considered. However, without the addition of TPBARs, which may be unacceptable from a regulatory or political perspective.

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\(^{183}\) Also see (Kovari et al., 2018).

\(^{184}\) Although tritium is not classified as a Special Nuclear Material; a category reserved for fissile materials such as plutonium, tritium production is monitored (but not safeguarded) by the IAEA and also subject to export control (British Government, 2012). Also see (Bergeron, 2002).

\(^{185}\) See “horizontal proliferation” – in which nuclear material developed for peaceful (commercial) purpose is transferred to be used for military purposes, or vice versa – in (Bergeron, 2002).
standpoint, tritium production is limited. As such, tritium from light water fission reactors was neglected. Tritium from non-CANDU sources – including Indian tritium and TPBARs – is further discussed in 6.3.6.3.

6.3.2.5. Total tritium supply

The supply of tritium from the three CANDU tritium producing countries is shown per individual nation in Figure 6-10. All plots account for decay but assume no supply (sale) of tritium, including for non-fusion demand.

![Graph of tritium generation rate](image)

*Figure 6-10*  Forecast estimating tritium generation for Canada, South Korea (scenarios 1 and 2) and Romania for the model time horizon.

6.3.3. Tritium demand

As detailed in 6.3.1, the two supply scenarios are modelled against two demand scenarios. The first considers only ITER demand starting in 2027, alongside a non-fusion demand of 0.1 kg/year. The second demand scenario accounts for the same demand as scenario 1 plus the tritium requirements of other selected public fusion programmes, fusion start-ups and scientific experiments. As such, a best-case and a worst-case estimate of available tritium are provided in the scenarios, respectively.

6.3.3.1. Demand from ITER

Nominal tritium quantities for ITER as detailed in (Glugla et al., 2007) were used but adjusted to reflect the current ITER schedule; tritium systems are commissioned in 2027, and full D-T operations start in 2035 (ITER Organisation, n.d.). Specifically, the model
assumes a 100g delivery of tritium to ITER in 2027 to be used for initial commissioning tests of the tritium systems, followed by a 200g delivery of tritium in 2030 for tritium system commissioning. Thereafter, tritium will be supplied from 2031 to 2034 at a rate of 800g per year to procure and build up the on-site operating inventory of tritium ahead of full D-T operation. From 2035, tritium is supplied at a rate of 1100g per year for a 12-year operation period. Tritium breeding in ITER is assumed to be zero.

6.3.3.2. **Demand from fusion start-ups**

It is assumed in demand scenario B that two to three private-sector fusion start-ups succeed in progressing towards full-scale fusion testing by 2030. It is estimated that each will require 0.5 kg of tritium over a 5-year period from 2025 prior to full-scale testing starting in 2030. The tritium requirement for full-scale testing is assumed to be analogous to that required for the fusion module described in (Menard et al., 2016), but over a shorter period. Menard et al. estimate tritium required for a full-scale test reactor between 0.4 and 0.55 kg per year for six years at full power. As before, it is assumed that two to three fusion start-ups all operating at a capacity factor of ~0.3 to ~0.5, and all require 0.475 kg per year for six years from 2030 as they accelerate from a prototype to a commercial fusion reactor (with tritium breeding capability) (Menard et al., 2016; Personal communication with David Kingham and Paul Thomas, Tokamak Energy, UK, 2017).

6.3.3.3. **Demand from domestic public fusion programmes**

Tritium demand from independent government projects scheduled to run in parallel to ITER is also considered. The Chinese Fusion Experimental Test Reactor (CFETR) is expected to demonstrate full breeding capability but will still require a start-up inventory of 2-3 kg when it begins operation in 2035\(^\text{186}\) (Personal communication with Jiangang Li, Chinese Academy of Sciences, China, 2017). Similar quantities of tritium are expected to be required for the Korean K-DEMO reactor, which will begin operation two years later in 2037 (ITER Organisation, 2013).

6.3.3.4. **Demand from other scientific endeavours**

Much smaller quantities of tritium required for scientific experiments taking place over the next decade were also considered to contribute to tritium demand and have been included

\(^{186}\) Despite the fact that China has the capability to produce tritium from its heavy water reactor at Qinshan (World Nuclear Association, 2020b), or perhaps via TPBARs, it is assumed that China will source tritium from the global stockpile, perhaps most likely from South Korea.
in both supply scenarios. Although the tritium needs of such experiments are negligible, they are included for completeness, see (Pearson, Antoniazzi & Nuttall, 2018).

6.3.4. Results

The results in Figure 6-11 and Figure 6-12 show the effects of modelling supply scenarios 1 and 2 against demand scenarios A and B. Figure 6-11 separates the total annual tritium production from the tritium consumption to better demonstrate the impact of both the supply and demand scenarios being modelled. The peaks at 2035 and 2037 are the quantities required for the K-DEMO and CFETR tokamaks. The decline in the demand around 2048 marks the end of ITER’s experimental programme.

Figure 6-11  Forecast of global tritium supply and demand.

Figure 6-12  Global tritium inventory for model scenarios. Supply scenarios 1 and 2 are plotted against demand scenarios A and B.
The information presented in Table 6-3 shows the tritium available for a next-step device based on the current ITER schedule, based on the two supply and two demand scenarios.

<table>
<thead>
<tr>
<th>Demand Scenarios</th>
<th>Tritium available for next-step devices (supply scenario 1)</th>
<th>Tritium available for next-step devices (supply scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand A (ITER only)</td>
<td>15.3 kg</td>
<td>27.6 kg</td>
</tr>
<tr>
<td>Demand B (additional demand)</td>
<td>12.2 kg</td>
<td>24.6 kg</td>
</tr>
</tbody>
</table>

Table 6-3 Available global tritium inventory for a next-step fusion device starting in 2054 based on ITER starting full D-T operation in 2035.

6.3.4.1. Modelling a 5-year delay to the ITER schedule

Scenarios for the ITER schedule, but with a “5-year slip” (first tritium in 2032, full D-T operation in 2040), were also modelled to capture any later start of D-T operations in ITER thereby accounting for any future schedule change, as shown in Table 6-4. It is assumed that the next-step device slips by three years to 2057 rather than by five years to 2059 (as 2057 is the time horizon of the model).

<table>
<thead>
<tr>
<th>Demand Scenarios</th>
<th>Tritium available for next-step devices (supply scenario 1)</th>
<th>Tritium available for next-step devices (supply scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand A (ITER only)</td>
<td>10.1 kg</td>
<td>22 kg</td>
</tr>
<tr>
<td>Demand B (additional demand)</td>
<td>7.6 kg</td>
<td>19.4 kg</td>
</tr>
</tbody>
</table>

Table 6-4 Available global tritium inventory for a next-step fusion device starting in 2057 based on ITER starting full D-T operation in 2040 (5-year delay to current ITER schedule).

6.3.5. Analysis

6.3.5.1. Tritium for ITER

Figure 6-11 suggests that even in the worst-case scenario, Canada is capable of supplying all tritium for ITER operation. However, net tritium production from Canada during the period in which it will supply ITER is close to zero (see supply scenario 1 in Figure 6-11),
and thus Canadian contribution to the global tritium inventory during this period is minimal, meaning no additional tritium is diverted to storage, which may have a knock-on effect for a next-step device. South Korea and Romania are thus deemed to be critical drivers in replenishing the global tritium inventory, as they are crucial for building up inventory to ensure tritium is available for a next-step device, as illustrated in supply scenario 2.

6.3.5.1.1. Romanian tritium for ITER

The Romanian tritium study found that Romania could supply tritium at a rate of 250g of tritium every year from 2027 (ITER start) until 2050, as shown in Figure 6-13. Romania is therefore potentially a valuable source for fusion projects requiring smaller quantities of tritium in the future, such as fusion start-ups.

![Tritium inventory CTRF with 250g per year supplied to fusion efforts](image)

6.3.5.2. The longer-term perspective: Tritium for next-step fusion reactors

Comparing the information in Table 6-3 and Table 6-4 indicates that if the ITER schedule slips and the start of a next-step fusion device are delayed, the quantity of tritium available for the start-up will be significantly less. Based on the results of the model, on the current ITER schedule, there is expected to be between 12.2 kg and 27.6 kg tritium left available for a next-step device. While the consequences of a 5-year slip to ITER’s schedule would not likely affect the ITER mission itself, it may mean only as little as 7.6 kg of tritium is left available for the start-up of a next-step device in 2057. Therefore, any further slip to ITER is unacceptable.
As detailed in 2.3, several nations are now pursuing their own next-step fusion programmes (see Figure 2-6). In reality, therefore, there are likely to be several fusion reactor projects advancing in parallel in the 2040s and 2050s. Moreover, this is not including the potential rise of fusion start-ups, all of whom may require substantial quantities of tritium. As such, even if tritium is available after the operation of ITER, the threat is that the competition for tritium will be significant. This may restrict international trade of tritium whereby tritium-producing nations halt the export of tritium in favour of supporting domestic missions, see (Arnoux, 2014). For South Korea to secure K-DEMO, it may restrict sales of tritium from the WTRF. Similarly, the conclusion that Romania could supply a fusion programme with 250 g tritium continuous supply for 25 years (see Figure 6-13) is of potential strategic significance, as a future DEMO developed by the European Union may be able to depend solely on the Romanian CTRF. If several reactors require tritium in the order of more than several kilograms, then the external supply of tritium for fusion may be insufficient beyond 2050. To ensure the success of a next-step fusion device, the development and demonstration of tritium breeding technology must be accelerated – there cannot be any dependence on external CANDU tritium. The prospect of supplying tritium for future fusion devices should be seen as both a current and future issue and necessitates a well thought out strategy on tritium supply and related R&D to resolve the tritium breeding problem.

6.3.5.3. Near-term perspective: Tritium for fusion start-ups

Despite the fact that in the longer-term tritium supply is uncertain, in the near-term, at least perhaps the next 15 years or so, tritium is abundant. This is particularly so due to the delays to ITER; which will be a heavy tritium user. Further, it is also possible to suggest with reasonable certainty that existing CANDU reactors and TRFs will continue operation and thus continue to produce tritium. Finally, tritium – decaying at 5.47% per year – is available from the current stockpile. Finally, as regards size, near-term fusion reactors that are of lower power and thus require less tritium – particularly they do not breed tritium – are favourable (Menard et al., 2016; Zheng et al., 2016). Typically, fusion start-ups are exploring lower power devices that will require less tritium in the development phase compared with ITER. As such, fusion start-ups have a window of opportunity to obtain tritium whilst it is readily available, at least until the operation of ITER.

6.3.6. Discussion

6.3.6.1. Accessibility, transport and delivery of tritium

Previously, the results of the model were analysed to assess quantities of tritium that may be available at future dates when fusion requires it, and more specifically the quantity that
will remain for the start-up of next-step device. However, the availability of tritium is not the same as access to tritium. In reality, it might not be possible to extract all the tritium from existing storage vessels. For example, where 1 kg of tritium might physically be available in a set of storage containers at DTRF, issues with extracting that tritium from the storage medium might mean that only, for instance, 800 g of that tritium is actually obtainable. As such, the quantities available, as shown in the model, is optimistic. Further issues, including the international transport and trade of tritium, are explored in section 5.1 of the PhD researcher’s publication in (Pearson, Antoniazzi & Nuttall, 2018)\(^\text{187}\).

### 6.3.6.2. Challenges relating to security and non-proliferation in the use of tritium for fusion

The model presented in this research assumes a hypothetical global tritium stockpile that is available for all activities. As suggested in 6.3.5.2, tritium-producing nations may look to preserve domestic tritium resource and could limit the projected quantities available for international use. Tritium being transported between countries will likely require nuclear trade agreements as well as compliance with the IAEA regulations relating to the safe transport of radioactive materials (IAEA, 2008). Furthermore, each party must satisfy the import and export controls of the appropriate countries. Tritium, as well as tritium facilities, plants and equipment are subject to export controls per (British Government, 2012; Canadian Nuclear Safety Commission, 2000). Additionally, because of fears of radioactive releases or theft, public pressure may also impact large scale international shipment of tritium. As such, these issues may present an additional hurdle in future trade of, and access to, the global tritium inventory. In particular, such issues may be particularly difficult for private-sector fusion start-ups without government backing.

In addition to concerns over international trade of tritium, the use of tritium in fusion must also be considered as a barrier to development. The long-term tritium economy must be balanced and controlled, but from a technical standpoint – for the start-up of fusion reactors – a surplus of tritium is both desirable and necessary. However, from a regulatory perspective, large quantities of tritium in storage at fusion power plants represents a risk (Klein, Poore & Babineau, 2015). Tritium that exists in large and readily usable quantities is cause for concern due to the fact that tritium is used as a booster in nuclear weaponry (Galeriu & Melintescu, 2013; Klein, Poore & Babineau, 2015; U.S. Department of Defense, 1998). The potential for fusion as a tritium-producing technology represents a challenge to commercial fusion, as it is feasible that fusion reactors could be diverted to produce tritium

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\(^{187}\) Not included in this thesis as it was the contribution of Dr Armando Antoniazzi (Kinectrics Inc.)
for military tritium. This issue must be considered and resolved for a future commercial fusion programme.

6.3.6.3. Issues relating to tritium from non-CANDU sources

Even though supply from CANDU is uncertain, the existing stockpile is estimated to be sufficient until the end of ITER operation, even in the worst-case scenario (see Table 6-4). However, the results also show that global tritium inventory begins to decline from as early as 2025, after which CANDU tritium is not able to replenish inventory stocks due to increased demand. As such, non-CANDU tritium producing options may need to be deployed in the future but will come with challenges relating to economics, regulation, and political and public acceptance.

China produces a small quantity of tritiated water at Qinshan (CANDU plants) and is exploring alternative methods of commercial tritium production (World Nuclear Association, 2020b; Ni et al., 2013). Similarly, as detailed in 6.2.5, India produces a significant quantity of tritium in its heavy water reactors. However, a key obstacle is that India operates eight heavy water reactors outside the IAEA safeguards regime (World Nuclear Association, 2020c; U.S. Department of Defense, 1998; Hindu, 2006). If a need arises and international agreements can be reached, it is estimated that with a 7 to 10 year lead time, India could commission a TRF specifically to support fusion development. However, it is most unlikely that nations that are signatories to the NPT would enter into commercial arrangements for tritium from India; not a signatory of the NPT. Among the regulatory issues, in Europe at least, could be the need for a formal justification to assess whether expected public benefits outweigh the radiological risks, the cost of the endeavour, and the geopolitical ramifications. Such an assessment could be difficult to achieve sufficient to grant permission.

While the addition of TPBARs to existing reactors might be unfavourable due to the association with weapons production of tritium, a purpose-built water reactor might become an attractive option for the supply of tritium for fusion in the case that CANDU supply is depleted. In particular, two approaches might be suitable. The first is that conceptual designs for an advanced gas-cooled reactor capable of supplying tritium at a rate of up to 8 kg per year have been developed by Japanese scientists, see (Nakaya et al., 2015). The second is that a CANDU reactor specifically for tritium production could be commissioned or repurposed specifically for the dual production of tritium and energy. Whilst it might seem unlikely that plant operators would be compelled to embark on tritium production, dual-purpose nuclear reactors, e.g. for isotope production, provide pedigree. For example, Bruce Power CANDU reactors in Canada have produced Co-60, and there are plans to develop the capability to produce Lu-177 (Bruce Power, n.d.). Similarly, OPG in Canada is embarking on a mission to produce Mo-99 from its Darlington CANDU reactors (Ontario
Power Generation, 2018). Despite this, given the regulatory hurdles that would need to be overcome for any purpose-built tritium generation, which may – along with construction costs – render the resulting tritium uneconomic for the fusion community. Furthermore, all routes to increasing tritium capacity would require a new nuclear fission reactor to be commissioned (or repurposed) specifically for the purposes of fusion. Currently, tritium must be removed from heavy water for a reactor for reasons relating to safety, and tritium is considered a by-product. This is an important distinction versus a purpose-built reactor, which would highlight the dependence of fusion on fission which may be detrimental from the perspective of public acceptance.\footnote{The PhD researcher also argues that fusion should heed the mistakes of the fission industry as regards public perception, see (Pearson, Bluck & Murphy, 2017).}

**6.3.6.4. Helium-3 production from tritium in Romania**

The case study on Romanian tritium production also explores the opportunity to produce helium-3 as an additional isotope from the decay of tritium. Helium-3 was assessed to be a lucrative hedging option in the case of no tritium sales. The results and analysis from the helium-3 study are not included here as they are not directly relevant to this thesis. However, it is noted that – in part motivated by the results of this research – that the technical design of the CTRF is now being updated to include the capability for helium-3 extraction (including a patent for helium-3 extraction), see (Stefan et al., 2019).

**6.3.6.5. D-D start-up and the need for tritium breeding**

Although it is likely that at least small quantities of tritium will be available for any fusion reactor start-up following the operation of ITER, alternative strategies to commission fusion reactors may be required. The possibility of commissioning fusion reactors using D-D fusion, i.e. no external tritium, is considered as a potentially viable route to reactor start-up. It is particularly important in the case of multiple reactors being built. Small quantities of tritium are still required to commission the isotopic tritium separation systems (~100 g) regardless of the tritium required to fuel the D-T reaction. Previous analyses on the possibility of D-D start-up suggest it is possible to build up a tritium inventory to begin full D-T operation in timescales in the order of months (Zheng et al., 2016; Konishi, Kasada & Okino, 2017). In reality, the situation in which zero external tritium is unavailable is unlikely, and it might be possible to start with, e.g. 10% tritium rather than zero. The introduction of a small quantity of tritium may accelerate the time to 50% D-T whilst being less dependent on externally-sourced tritium (Kwon, Kasada & Konishi, 2013; Konishi, Kasada & Okino, 2017). A D-D start-up regime – possibly with limited quantities of external tritium – may

\footnote{The PhD researcher also argues that fusion should heed the mistakes of the fission industry as regards public perception, see (Pearson, Bluck & Murphy, 2017).}
thus present the only realistic option for the commissioning of multiple reactors simultaneously. Regardless, such an approach requires the establishment of tritium breeding technology. The development of breeding blanket technology is hence discussed as a critical challenge to the commercialisation of fusion in Chapter 7.

6.3.7. Conclusions

A forecast of the tritium supply and demand for fusion is presented. The results of the model suggest that tritium from CANDU is likely to be readily available for fusion R&D over the next two decades until the beginning of ITER, which will start full operations in 2035. ITER will subsequently require a significant proportion of the available global tritium inventory. Combined with a potential increase in the competition for tritium to support several concurrent next-step fusion reactors, the quantity of tritium available for next-step devices starting around 2050 may be limited. In such a scenario, Romania and South Korea might prove to be key tritium suppliers. However, tritium suppliers may choose to support domestic programmes over international ones resulting in a future in which global tritium supply is strained, perhaps necessitating the commissioning of alternative routes to produce tritium (including some which are unfavourable). In particular, much like deuterium, tritium is not without issue from the perspective of regulation and non-proliferation. Whilst not insurmountable, the issues relating to the supply and use of tritium indicates that fusion is likely to be (and needs to be) scrutinised in the near future.

Fusion start-ups have a window of opportunity to 2035 in which tritium is readily available to support their accelerated development programmes. Furthermore, if fusion start-ups can pursue designs that require less externally-sourced tritium, or if they can develop tritium breeding blankets for near-term reactors on their development programmes, then fusion start-ups may offer an optimal route to commercial of fusion from the perspective of tritium supply. However, the same regulatory and geopolitical constraints will apply to fusion start-ups, which should be understood as a significant barrier to their plans for commercialisation.

6.4. Chapter Summary

The analysis of deuterium supply in the context of fusion in this thesis represents the first such instance in the literature. It is concluded that whilst the availability of deuterium, as well as production and cost, are unlikely to present a significant barrier to commercial fusion, issues surrounding the supply and trade of deuterium may require a regulatory hurdle. This research presents a new model estimating future tritium availability and supply. Principally, in the time leading up to full D-T operations in ITER, tritium is readily available. Beyond ITER, a variety of factors relating to tritium supply – including lack of availability due to competition and increased regulation – could hinder the commercial development of fusion.
Regardless of the situation, however, it is concluded that the development and proven function of tritium breeding blankets represents the most significant challenge to be overcome. Blankets must be developed as soon as possible and while external tritium is available for testing.

In part, this chapter has addressed research question 3. However, the contributions from the research in Chapter 7 are required to fully address the research question. Conclusions from Chapter 6 and 7 will thus be collated in Chapter 8.

6.5. **Resources for tritium breeding blankets**

Tritium supply is an issue relevant for the R&D stage of fusion development, up to the very beginning of a commercial fusion programme, including perhaps even for FOAK reactor commissioning. However, as shown in this chapter, tritium is not considered as the primary fuel for a commercial D-T fusion programme. Even an assessment of lithium, which is the primary fuel and often referred to as the key resource for fusion reactors, is not sufficient. Instead, all the resources required for tritium breeding blankets should be considered as fuels. Chapter 7 of this thesis thus explores the availability, supply and use of what are identified as critical blanket resources: lithium, beryllium, lead and helium. Each resource is assessed from the perspective of its impact on the commercial development of fusion, in a similar way that which deuterium and tritium have been assessed in this chapter.
Chapter 7. Availability, supply and use of critical natural resources for commercially viable tritium breeding blankets

As detailed in Chapter 6, tritium breeding blankets are a critical technology that must be developed for the realisation of commercial fusion. Breeding blankets are the subject of dedicated R&D in institutions around the world. However, most programmes are focused on overcoming technical challenges and not on commercial drivers. A specific commercial challenge relates to the availability, supply and use of blanket resources. Whilst fusion resources are often described as ubiquitous; it is contended that this is an oversimplification predicated on the abundance of both deuterium (6.1.1) and lithium in seawater. Absolute resource availability, i.e. abundance, is not the same as supply, which relates to the flow of resource. Furthermore, whilst lithium can be considered as the primary resource required to produce tritium, there are several other resources essential for a tritium breeding blanket that can similarly be considered “fuels” as they are consumable, i.e. they are used up. These are considered to be lithium (specifically lithium-6), beryllium, lead and helium.

The structure of this chapter is as follows. 7.1 provides a brief introduction to tritium breeding blankets. 7.2 provides a review of the literature on the identified resources. Subsequently, a model forecasting the commercial rollout of fusion is detailed in 7.3 and 7.4. The results of the model are analysed, and issues discussed in 7.5. Finally, the findings from the research are used to outline a commercially optimal blanket in 7.6.
7.1. **Introduction**

This section briefly describes the function of tritium breeding blankets before summarising the current status of blanket technology development in fusion research. The rationale as to why natural resources for tritium breeding blankets are critical to the commercial success of fusion will hence be outlined.

7.1.1. **Tritium breeding blankets**

Under neutron interaction, isotopes of lithium-6 and lithium-7 can undergo fission to produce tritium. Tritium breeding blankets (hereafter abbreviated to TBB) are designed to surround a fusion reactor to allow the neutrons to produce tritium. The mechanism for tritium production from lithium is shown in equations 7.1 and 7.2.

\[
\text{Eq. 7.1} \quad ^{6}\text{Li} + n \rightarrow ^{4}\text{He} + ^{3}\text{H} + 4.78 \text{ MeV}
\]

\[
\text{Eq. 7.2} \quad ^{7}\text{Li} + n \rightarrow ^{4}\text{He} + ^{3}\text{H} + n - 2.47 \text{ MeV}
\]

To produce enough tritium to sustain a D-T fusion reactor, for every neutron produced from a D-T fusion reaction, one lithium atom must be fissioned to produce one tritium atom. The ratio of neutrons produced in a TBB to that used up in a fusion plasma is defined as the tritium breeding ratio (TBR). A TBR greater than one will allow the fusion reactor to be self-sufficient on tritium, i.e. no external tritium is needed (see 6.3.6.5). Due to the nuclear properties of lithium, at D-T fusion neutron energies (14 MeV), the isotope lithium-6 has a higher affinity to fission to produce tritium than lithium-7. However, lithium-6 makes up only 7.4% of natural lithium. As such, a TBB made of natural lithium cannot achieve a TBR of above unity (Fischer et al., 2016). The neutron yield must, therefore, be increased by enriching lithium in lithium-6. However, principally due to the space required in the fusion reactor vessel for other systems, e.g. diagnostics (see TGI #4 in Table 4-4), which thus limits the space available for tritium breeding, lithium-6 enrichment alone is not enough. As such, specific elements with special nuclear properties that can increase the number of neutrons – called neutron multipliers – can be used to increase the neutron yield. A neutron multiplier produces two or more neutrons following interaction with a single neutron interacts with it, via an (n,2n) fission reaction. Neutron multipliers can be used in conjunction with lithium-6 enrichment to increase TBR above unity. The two most common neutron...
multipliers used in TBB designs are beryllium and lead\textsuperscript{189}, for which the (n,2n) reactions are shown in equations 7.3 and 7.4\textsuperscript{190}.

\begin{align*}
\text{Eq. 7.3} & \quad _{4}^{9}Be + n \rightarrow 2\ _{2}^{4}He + 2n \\
\text{Eq. 7.4} & \quad _{82}^{209}Pb + n \rightarrow 2\ _{81}^{208}Tl + 2n
\end{align*}

The choice of neutron multiplier greatly affects TBB design and the associated technology development challenges. The neutronic properties of beryllium and lead also determine lithium-6 enrichment (Fischer \textit{et al.}, 2016; Abdou \textit{et al.}, 2015). While both types of TBB require some level of lithium-6 enrichment, the nuclear properties of lead necessitate much higher enrichment than beryllium, typically 90% and 30% respectively. Finally, to remove the heat generated in the blanket, and to transfer it into usable energy, TBBs must be cooled by a fluid. Both lead-based and beryllium-based blanket concepts can utilise water or helium as a coolant (Ihli \textit{et al.}, 2008; Abdou \textit{et al.}, 2015). In summary, the resources required for TBBs are not just lithium, but also lithium-6, beryllium or lead as a neutron multiplier, and helium or water as a coolant\textsuperscript{191}.

\subsection*{7.1.2. Tritium breeding blanket development}

The need to breed tritium has been well understood since the earliest days of fusion research (see (Impink, 1965; Allibone, 1959)). Since then, TBBs have been the focus of several dedicated R&D programmes, and numerous blanket designs have been developed. However, TBBs have not been tested in a fusion environment beyond laboratory-scale, i.e. TRL 2 to 3. Simply, this is because no fusion reactor has operated at a sufficient level of performance for testing in a relevant environment. The expectation is – and has long been – that ITER will provide the first testing of TBB designs via its tritium breeding module (TBM) programme. However, due to delays to ITER, it is thus likely to be more than 15 years before the current TBM designs are tested, validated and improved for a next-step (DEMO) device. Ostensibly, with the technology at a low TRL with no means to develop further until testing is complete, the focus has been on developing and proving technical feasibility via a series of non-fusion reactor experiments. For example, Abdou \textit{et al.} and Federici \textit{et al.} detail experiments to prove material performance, tritium extraction and efficient heat removal are focal points of current blanket development (Abdou \textit{et al.}, 2015; Federici \textit{et al.},

\textsuperscript{189} Uranium and graphite are alternative neutron multipliers, see (Manheimer, 2018; Ma \textit{et al.}, 2014).

\textsuperscript{190} Isotopes of Pb other than \textsuperscript{208}Pb also undergo an (n,2n) reaction, but create different fission products.

\textsuperscript{191} Structural materials are discussed in 7.2.2.
As alluded to in Chapter 2 of this thesis, technologies are not technologically perfect or “market-ready” at the beginning of development. Some commercial issues have been highlighted in the literature – see (Federici et al., 2016; Hernández et al., 2017; Fischer et al., 2009)) – but such issues are often depicted as problems to be solved later, where later is likely to be after initial tests on ITER TBMs, i.e. around 2040 or later. Whilst the development of blanket technology has had a natural commercial emphasis in so much that designs that are safe to operate and produce enough tritium for a reactor to be self-sufficient are being pursued, the longer-term commercial drivers have not been central to development.

Based on the findings presented in Chapter 2, it is contended that the development of TBBs – with R&D predominantly taking place on government-led programmes, typically by national laboratories – is a manifestation of the linear model of innovation. Long-term commercial drivers must be used to inform near-term development, lest a technological solution – no matter how high performance – will not succeed in the market. The commercial challenges must, therefore, be understood so that an optimal design for a TBB, one which is both technologically and commercially viable, can be developed.

7.1.3. Natural resources for fusion: vital for commercial viability

Wellmer identifies a common trend across several new energy technologies in which demand for resources is increasing in areas that have traditionally seen less demand (Wellmer et al., 2018). For instance, the lithium industry is already experiencing issues scaling-up to match battery demand for cars (Agusdinata et al., 2018). Hence, how or whether demand for such materials can be met is likely to be a limiting factor in the rapid and effective deployment of new energy technology, including fusion. The costs associated with the development of TBBs is currently dominated by the R&D cost, i.e. experimentation, development and qualification of new materials, computer modelling etc. However, in the latter stages of development – production – the raw material costs and manufacturing costs become significant (Prior et al., 2013). In the long-term, therefore, the material costs of TBBs are likely to make up a significant fraction of the total cost, as in (Abdou et al., 2007).

Commercial challenges extend beyond the cost of resource. Bradshaw et al. explore the broad concept of the sustainability of fusion, see (Bradshaw, Hamacher & Fischer, 2011). The study identified that there were resource limitations and supply constraints associated with key resources required for TBBs in particular. Whilst the study uncovered the problem, it was carried out with limited depth. Other studies on TBB resources are less comprehensive, see (Tokimatsu et al., 2003; Hamacher et al., 2001; Ward, 2007; Sánchez, 2014; Kembleton, 2019; Von Hippel et al., 2012). However, one study which provides a greater level of depth is a 1978 study by Rhinehammer and Wittenberg (Rhinehammer &
Wittenberg, 1978). Whilst providing valuable insights – which will later be referred to – the study is over 40 years old and in need of updating. In summary, the availability, supply and use of resources for TBBs presents a gap in the literature that must be explored.

7.2. Literature review of natural resources for tritium breeding blankets

7.2.1. Previous literature on resources for tritium breeding blankets

A review of the aforementioned literature on the availability and supply of natural resources highlights several resources as a concern: lithium-6 (enriched lithium), beryllium, lead, helium, and structural materials\textsuperscript{192} such as silicon carbide as well as a group of fusion-grade steels collectively known as RAFM (Reduced Activation Ferritic-Martensitic) steels. Interestingly, many of the same resources – particularly lithium (and lithium-6), beryllium, lead and helium, as well as deuterium and tritium (see Chapter 6) – were identified as potential problems by Rhinehammer and Wittenberg (Rhinehammer & Wittenberg, 1978); although the study is over 40 years old, many of the problems are still relevant. Whilst this might indicate that there has been limited progress in finding solutions to these problems, the fusion programme has not yet moved beyond the R&D stage and thus – despite seemingly out of date – they can still be considered as future problems to be solved later. Accordingly, it is found that all existing assessments collectively acknowledge the problems, and many do not provide deeper understanding or solutions to the problems.

7.2.2. Critical resources for tritium breeding blankets

All the resources detailed in 7.2.1 are important for the development of a TBB. However, the focus of this research is on resources for which there is no other alternative, i.e. it cannot be substituted for another resource and is thus critical. Further, all the resources explored here are considered as consumables, i.e. they have to be replaced periodically, as they are used up. Accordingly, the resources of interest are lithium (specifically, lithium-6) as the primary fuel to produce tritium and which is burnt up in that process; beryllium or lead as essential neutron multipliers for increasing the neutron yield\textsuperscript{193}, which also burn up during

\textsuperscript{192} Blanket concepts require structural materials to form the structure to house the lithium breeder and neutron multiplier, as well as channels designed to carry the working fluid in the blanket, see (Abdou et al., 2015).

\textsuperscript{193} Uranium can be used as a neutron multiplier but it is considered unviable due to links to proliferation, see footnote 189.
the process; and helium as a coolant that is necessary for high-temperature and thus high efficiency\textsuperscript{194}, which is subject to leakages and must be topped up.

Structural materials for blanket systems, including silicon carbide, are not included in this research as the assumption is made that materials that could achieve the appropriate performance for efficient blanket operation already exist. Grades of steel that are used in conventional fission reactors could be used for the structural materials for a fusion reactor, for example. Whilst they would also degrade over time, unlike advanced materials under development, they are readily available. The rationale to avoid such structural materials for fusion reactors is that they contain isotopes that produce nuclear waste, whereas advanced reduced-activation steels and silicon carbide avoid the production of such long-lived waste (Klueh & Nelson, 2007)\textsuperscript{195}. However, such advanced materials are not tested at scale, have limited supply chains and are typically expensive.

Finding a structural material that is most practicable in the near-term, even if it results in the production of nuclear waste, would facilitate faster commercialisation. Conversely, waiting for an optimal material to be developed could delay it. Practicality is more important in the early stages of development, and better technologies can be developed later. As such, consideration of the availability and supply of structural materials for TBBs is excluded from this research, and materials such as those described in (Klueh & Nelson, 2007) are assumed to be available.

In summary, a review of the fusion literature on the availability, supply and use of resources for TBBs highlights the following issues relating to lithium-6, beryllium, lead and helium:

- Lithium is abundant, and production is ample, but lithium-6 production is effectively zero. The cost of natural lithium is low, but the cost of lithium-6 is potentially high.
- Beryllium resource is not abundant on Earth. Moreover, the supply chain capability of beryllium appears limited against the requirement for fusion in the near- to mid-term.

\textsuperscript{194} Water as a coolant limits the performance to that of a PWR, with a maximum operating temperature in the region of 350°C, see (Tillack \textit{et al.}, 2015).

\textsuperscript{195} RAFM steels typically replace solutes in steels that produce radioactive isotopes with others that do not result in the production of long-lived nuclear waste, e.g. molybdenum and niobium are replaced by vanadium and tungsten (Zinkle & Busby, 2009). Similarly, silicon carbide is a desirable structural material for fusion reactors as it is transparent to neutrons and thus can facilitate longer lifetimes for components, but the material has not yet been successfully developed, see (Snead \textit{et al.}, 2011).
Lead resource is ample, but the use of lead in fusion creates long-lived isotopes. Lead also requires high levels of lithium-6 enrichment (see above).

Helium resource is limited and expensive. It has recently been characterised in detail in the context of fusion (detailed in 7.2.6).

A literature review on the four resources is necessary to understand the areas identified by the high-level studies in greater depth so that research gaps can be identified. A literature review on lithium, beryllium, lead and helium is detailed in 7.2.3 through 7.2.6.

### 7.2.3. Availability, supply and use of lithium

#### 7.2.3.1. Abundance of lithium

Lithium is the third lightest element in the periodic table and is considered abundant on Earth with a crustal abundance of 60 ppm (Fasel & Tran, 2005). The terrestrial resource base of lithium and discovered economic reserves\(^ {196} \) are estimated at 70 MT and 14 MT\(^ {197} \), respectively (U.S. Geological Survey, 2019c; Yongliang et al., 2012). The majority of lithium resource is mined from salt brines under salars in North America and South America or as pegmatite ore in China and Australia (Yongliang et al., 2012; U.S. Geological Survey, 2019c; Fasel & Tran, 2005; Bradshaw, Hamacher & Fischer, 2011). Lithium is also abundant in seawater, with a concentration of 0.17 ppm (0.17g per tonne). The total quantity of lithium contained in the world’s oceans is estimated at 226,000 MT (Bradshaw, Hamacher & Fischer, 2011).

#### 7.2.3.2. Lithium supply and demand

Combined, Australia, Chile and Argentina produce over 85% of the world’s lithium, with the vast majority from Australia. Lithium, as a terrestrial resource, has been heavily explored for the lithium-ion battery industry, particularly in recent years for electric vehicles (Egbue & Long, 2012; Sonoc, Jeswiet & Soo, 2015; Prior et al., 2013). Estimates for the global lithium resource base were 25 MT in 2010. The substantial increase in the resource base (to 70 MT) is due to increased exploration to match the surge in demand for lithium for battery

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\(^ {196} \) “Reserves” are defined as proven deposits that can be extracted economically at the present time. “Resource base” is defined as the concentration of a given material in a form and quantity that it is potentially extractable, but not economically at the given time. Resources in seawater and air are often provided as a “backstop” but are not included in terrestrial resource estimates. See (U.S. Geological Survey, 1980).

\(^ {197} \) Not including U.S. reserve estimates, which are withheld for strategic purposes.
technology. Similarly, the supply of lithium products has trebled in the past five years from 30,000 to 85,000 tonnes per year (compare (U.S. Geological Survey, 2014) and (U.S. Geological Survey, 2019c)).

It is expected that the demand for lithium for batteries will continue to drive an increase in the capacity of the lithium industry supply chain. Bradshaw et al. estimate that if one billion cars were electrified over the next 40 years, 10 MT lithium would be required; substantially below the current resource base estimate, and now below the estimate for economically extractable lithium (Bradshaw, Hamacher & Fischer, 2011; U.S. Geological Survey, 2019c). To this end, Tesla is developing a “Gigafactory” with a targeted processing capacity of 5000 tonnes per year (Tesla, n.d.). In addition to lithium for cars, the use of lithium for grid storage could cause demand to increase substantially. In consequence, recycling may become ubiquitous. However, the process is currently uneconomical in spite of the price of lithium (ore) increasing from US$ 6.70/kg to US$ 17/kg due to demand since 2014 (Gaines, 2014; Sonoc, Jeswiet & Soo, 2015; U.S. Geological Survey, 2019c).

7.2.3.3. Lithium for fusion

Estimates for lithium supply for fusion were made in the 1970s (see (Hartley, Gore & Young, 1978; Rhinehammer & Wittenberg, 1978)), and more recently in (Bradshaw, Hamacher & Fischer, 2011; Yongliang et al., 2012; Fasel & Tran, 2005; Ward, 2007). However, these studies must now be considered out of date due to the fact that the available resource base of lithium has almost trebled since the latest study was conducted. Forecast scenarios for the lithium required to support a fusion industry using 2012 data (U.S. Geological Survey, 2012) – where lithium reserves are estimated at 6 MT – are shown in Figure 7-1. In the worst-case scenario (no recycling and low resource estimates), fusion is limited to decades before lithium runs out if supplying more than 20% of primary energy.
However, results of the study by Bradshaw et al., which are based on the resource base estimates from 2011, suggest that the supply of lithium for fusion is ample even in the case of no recycling (Bradshaw, Hamacher & Fischer, 2011). Hence, given that the resource base and the reserves have increased considerably in the past ten years it is assumed that any problem with the supply of lithium resource can only have reduced since these projections were made. Moreover, Yongliang et al. assess lithium available in seawater for fusion and estimate that resource will last for several million years (Yongliang et al., 2012). Research into a cost-effective way to harvest lithium from seawater is being explored, see (Hoshino & Terai, 2011).

7.2.3.4. Lithium-6 for fusion

Despite lithium reserves appearing adequate to allow a future fusion industry to be considered sustainable, the supply of lithium enriched in lithium-6 – the isotope most important for breeding tritium – is effectively zero. Although almost all designs depend on the use of lithium enriched in lithium-6 (see (Abdou et al., 2015)), potential problems associated with the use of lithium-6 is limited in the fusion literature. Previous studies on the production of lithium-6 for fusion have suggested that depleted lithium from the fusion enrichment process could be diverted to be used in battery technology, as batteries are not dependent on any specific isotope of lithium (Von Hippel et al., 2012; Hartley, Gore & Young, 1978; Bradshaw, Hamacher & Fischer, 2011; Yongliang et al., 2012; Fasel & Tran, 2005). However, lithium-6 production is discussed (Von Hippel et al., 2012; Bradshaw,
Hamacher & Fischer, 2011). Even so, von Hippel et al. make a cost estimate for lithium-6 production\textsuperscript{198}, and neither publication discusses potential problems with the use of lithium-6 for fusion in-depth\textsuperscript{199}. Giegerich et al. highlight initial problems relating to the need to produce lithium-6 via a process avoiding the COLEX process. The COLEX process was used in the U.S. between 1954 to 1963 to produce 442 tonnes of lithium-6 but is now prohibited (by both the US Environmental Protection Agency and by the international Minamata convention) due to the large quantities of mercury that are produced in the process (U.S. Department of Energy, n.d.; Giegerich et al., 2016)\textsuperscript{200}.

The existing fusion literature does not discuss that lithium-6 and technologies for the production of lithium-6 are subject to export control (British Government, 2012; Canadian Nuclear Safety Commission, 2000). Lithium-6 is the other component of the Li\textsuperscript{6}D target in a thermonuclear weapon\textsuperscript{201} (Brooks & Southworth, 2011; U.S. Department of Defense, 1998). Other than for use in small quantities for scientific research, lithium-6 has only been produced in significant quantities – via the COLEX process – for military purposes, per (U.S. Department of Energy, n.d.). Therefore, in a similar way to deuterium, the export controls around lithium-6 for fusion and the links to proliferation presents a potential commercial challenge that has not been comprehensively considered.

7.2.4. Availability, supply and use of beryllium

7.2.4.1. Abundance of beryllium

Beryllium is the fourth lightest element in the periodic table. However, unlike lithium – a similarly light element – it is scarce on Earth. Beryllium’s crustal abundance is low, and

\textsuperscript{198} The method to obtain the cost estimate is not known.

\textsuperscript{199} During the final stages of this research, Giegerich et al. published research outlining key problems relating to lithium-6 production with a view to developing a novel lithium-6 production process (Giegerich et al., 2019). However, the research presented in this thesis is more focused on the commercial issues, e.g. cost, with reference to selected technical challenges explored by Giegerich et al and thus the researches are complementary.

\textsuperscript{200} Unless it has been produced in secret, lithium-6 production has not occurred in the U.S. since the closure of the COLEX plant at Oak Ridge National Laboratory in 1963.

\textsuperscript{201} The Castle Bravo thermonuclear bomb test used lithium enriched in lithium-6. Famously, scientists did not account for the contribution of tritium and the additional neutron from additional reactions with lithium-7, meaning that the yield from the explosion was significantly higher than calculated.
concentration in seawater is 0.0000006 ppm (5,000 times less than uranium concentration), and it is not viable to extract beryllium from the ocean (Emsley, 2011). The reason for the low abundance of beryllium is that, unlike other elements heavier than hydrogen and helium, beryllium is not produced in stellar nucleosynthesis (stellar fusion). Furthermore, beryllium-9 as well as lithium-6$^{202}$ (and boron-10) are not generated in the normal course of stellar nucleosynthesis and are, in fact, destroyed in stellar fusion. The graph in Figure 7-2 shows the abundance of elements in the universe in which lithium, beryllium and boron are anomalies in an otherwise downward trend from hydrogen. As shown, beryllium-9, in fact, has the lowest abundance of the three elements, and this is due to its nuclear cross-section, see (Read & Viola, 1984; Vangioni-Flam, Cassé & Audouze, 2000; Emsley, 2011).

Beryllium deposits exist all over the world, but the largest deposits exist in the United States. However, these vary in size and in grade. Typically, beryllium does not exist in large quantities in its ore form. The global resource base for beryllium is estimated at 100,000 tonnes, with the majority in the U.S. However, this figure does not include Chinese or Russian deposits. Furthermore, estimates are typically conservative as beryllium concentration in the ore is hard to predict, even for well-known reserves (U.S. Geological Survey, 2018; Personal communication with Steven Freeman and Phillip Sabey of Materion Corporation, U.S., 2018). Other estimates are higher; 485,000 tonnes (Dombrowski, 1997) and 400,000 (Emsley, 2011). Beryllium is most commonly mined as bertrandite ore in the form of beryllium oxide (BeO), and the average content of BeO in mined rock is 0.6% in the

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$^{202}$ Theory on stellar nucleosynthesis thus also explains why the abundance of lithium-6 is low, see (Vangioni-Flam *et al.*, 1999).
The largest known economic deposit is at Spor Mountain, Utah, USA, which contains approximately 20,000 tonnes beryllium (U.S. Geological Survey, 2019a). Larger deposits exist, but the ore concentration is low, and thus it is currently uneconomical to mine. As with all mineral commodities, exploration may yield the discovery of further deposits in the future. Estimates of beryllium deposits in the U.S. and around the world are shown in Figure 7-3.

![Figure 7-3: Estimates of grade and tonnage for beryllium deposits worldwide (diagonal lines show the equal value of contained beryllium in metric tonnes), reproduced under a Creative Commons license from (U.S. Geological Survey, 2018)](image)

### 7.2.4.2. Beryllium applications

Beryllium is one of the lightest metals but has a unique atomic structure that gives it high stiffness, a high melting point (1562 K), and the highest specific heat capacity of any metal (1925 J/kg·K) (U.S. Geological Survey, 2018). Accordingly, beryllium is used in a wide range of specialist applications, including in the defence and telecommunications industries. In particular, its high thermal diffusivity assures rapid temperature equalisation throughout the material, whilst retaining its strength, which makes it suitable for high-temperature applications. Beryllium also has unique nuclear properties. It has a high scattering cross-section which means under neutron irradiation neutrons are conserved rather than captured because of beryllium’s low thermal neutron capture cross-section (Boland, 2012).

### 7.2.4.3. Beryllium supply and demand

Materion Corporation (formerly Brush Wellman) is the largest beryllium mining company in the world. The company mines beryllium; processes it from its ore; and converts it into beryllium alloys, ceramics or pure metal and also processes externally sourced beryllium.
ore – international or domestic – to process it into beryllium products (Trueman & Sabey, 2014; U.S. Geological Survey, 2018). Beryllium is also an isotope of strategic importance, and the U.S. government holds a stockpile of beryllium, see (Trueman & Sabey, 2014; Boland, 2012; U.S. Geological Survey, 2019a). Materion also holds a central inventory which is topped up by newly mined beryllium, recycled beryllium and beryllium from the U.S. stockpile, all of which is processed at a processing facility in Ohio, U.S. Figure 7-4 shows the beryllium industry

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203 For a comprehensive overview of the beryllium industry, see (Trueman & Sabey, 2014).
Figure 7-4 Beryllium industry and the supply chain: location, production, refining and end-use. Created by the researcher with information from (Trueman & Sabey, 2014; U.S. Geological Survey, 2019a).
Henckens et al. study of critical materials suggest that beryllium supply is not of concern (Henckens et al., 2016). However, this may be due to the fact that the industry’s forecasts are based on near-term projections for demand. Beryllium suppliers consider current reserves to be capable of meeting future demand. For example, Materion expects to continue operating Spor Mountain as its central mining deposit until beyond 2050 (Personal communication with Keith Smith of Materion Corporation, U.S., 2018). Current production is 200 to 300 tonnes per year, but this rate is expected to increase to ~450 tonnes per year by 2030 (U.S. Geological Survey, 2018).

Figure 7-5 shows the production and price of beryllium between 1988 and 2017. The dip in production in 2001 was due to the shutdown of existing beryllium processing facilities to be upgraded. During this period, beryllium was mainly supplied to the market from the U.S. strategic stockpile (Trueman & Sabey, 2014). Although the beryllium price is set by suppliers via private contracts, its cost is derived principally by the cost of mining, refining and processing beryllium. The significant increase in price between 2005 and 2011 was driven by mining and refining cost factors, highlighting the volatility of the beryllium industry. In particular, an increase in the price of refining process chemicals, especially sulphuric acid, ammonia and diesel due to the financial crisis. The price of sulfuric acid increased ten-fold from under US$ 100 to over US$ 700 per tonne (U.S. Geological Survey, 2011). Similarly, the ammonia price trebled between , and the price of diesel fuel went from US$ 1.50/gallon to almost US$ 4/gallon between 2004 and 2011. The current market price of beryllium is US$ 530/kg, which is largely dependent on the cost of production.

![Beryllium production and price 1988 to 2017](image)

**Figure 7-5** Beryllium production and price 1988 to 2017, created by the author using data from (U.S. Geological Survey, 2017).

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204 Price from (U.S. Geological Survey, 2019a) as beryllium is not traded on global commodity markets and instead it is sold via privately agreed contracts.
7.2.4.4. **Beryllium for fusion**

The (n,2n) reaction in beryllium makes it a candidate to be used as a neutron multiplier in TBBs. Beryllium-based TBBs require lithium enrichment between 30 and 60%, depending on design (Abdou et al., 2015; Hernández et al., 2017). Figure 7-6 shows the EU helium-cooled pebble bed blanket concept.

![Image of a pebble bed blanket concept with a Creative Commons license from Hernández et al., 2017.](image)

**Figure 7-6** Helium-cooled pebble bed tritium breeding blanket design, reproduced under a Creative Commons license from (Hernández et al., 2017).

The requirement of fusion for beryllium is substantially greater than current supply capability, with a requirement of approximately 120 tonnes of beryllium per GWth (Bradshaw, Hamacher & Fischer, 2011; Personal communication with Aniceto Goraieb, Karlsruhe Beryllium Handling Facility, Germany, and Christopher Dorn, Beryllium4Fusion). In the near-term at least, the capability of the beryllium industry to supply small quantities for e.g. ITER test blankets is sufficient. However, in the long-term, the comparably great demand for beryllium by the fusion industry may represent an insurmountable issue due to the limited available beryllium resource. Accordingly, against the available resource base estimate of 100,000 tonnes, Bradshaw et al. estimate that existing global beryllium resources could not sustain beyond the first 1000 reactors of a commercial fusion programme (Bradshaw, Hamacher & Fischer, 2011). A substantial reduction is required in the quantity of beryllium resource required for fusion if beryllium-based TBBs are to be used for a commercial fusion programme. Whilst several studies acknowledge potential issues with beryllium – see (Kolbasov, Khripunov & Biryukov, 2016; Kembleton, 2019; Hernández...
et al., 2017; Federici et al., 2016; Ward, 2007) – a comprehensive understanding of the issues, and potential solutions to resolve it, represents a gap in the literature.

7.2.5. Availability, supply and use of lead

7.2.5.1. Abundance of lead

Lead is a heavy metal element that is abundant on Earth with a crustal abundance of 14 ppm. Lead occurs in high concentration deposits, typically in the form of Galena (PbS; 87wt% Pb), and is principally mined in China, Australia, Peru and the U.S. (Emsley, 2011). Current reserves are estimated at 83 MT, and the resource base is estimated at over 2 BT (U.S. Geological Survey, 2019b).

7.2.5.2. Lead supply and demand

Current global production of lead is 4.5 MT per year (U.S. Geological Survey, 2019b). A significant proportion of demand for lead is for use in lead-acid batteries (for automobiles), accounting for 86% of demand (U.S. Geological Survey, 2015). Although domestic consumption of lead in the U.S. in 2018 was 71% recycled lead, 20,000 tonnes are still mined each month, per the graph in Figure 7-7.

Figure 7-7  U.S. production of lead from July 2017 – July 2019, from (U.S. Geological Survey, 2019d).

Tokimatsu et al. erroneously cite the beryllium resource base as 100 million tonnes rather than 100,000 tonnes, see (Tokimatsu et al., 2003). This might explain why many in the fusion industry are unaware of beryllium supply as a potential issue.
7.2.5.3. Lead for fusion

Due to its nuclear properties, lead is not as effective a neutron multiplier as beryllium at fusion neutron energies (see (Fischer et al., 2016)). Therefore, it is necessary to have a higher level of lithium-6 enrichment – typically, 90%. Figure 7-8 shows two designs for lead-based TBBs.

![Figure 7-8](image)

Figure 7-8: Two views of the Dual-Cooled Lead-Lithium (DCLL) tritium breeding blanket (left – a cross-sectional view of a lead-lithium channel, right – full blanket module), reproduced with permission from (Malang & Schleisiek, 1994; Tillack & Malang, 1997).

Approximately 1,700 tonnes of lead is required per GWth for lead-based TBBs (Bradshaw, Hamacher & Fischer, 2011). Compared to the supply capability in the U.S. alone, and the overall resource base of 2 BT, the availability and supply of lead for fusion does not present a problem. However, while lead is abundant and readily available in sufficient quantities for fusion, there are several challenges with the use of lead for TBBs. Firstly, it is important to note that there are several significant technical issues with the use of lead-based TBBs, in particular, the flow of lithium-lead eutectic in strong magnetic fields and tritium extraction, see (Ihli et al., 2008; Abdou et al., 2015). However, assuming such technical issues can be overcome, there are additional issues that relate to the commercial viability of lead-lithium blankets – for example, the use of lead results in the production of actinides from neutron irradiation. Polonium-210 and Mercury-203 are created under neutron interaction with Bismuth-209 (which is produced from naturally occurring isotopes of lead), as well as Lead-205. These isotopes must be isolated and removed (Gohar & Smith, 2000; Li Puma et al., 2006). As such, the use of lead-based TBBs represents a potentially unacceptable long-term waste handling issue. Furthermore, there is no existing supply chain to manufacture lithium-lead eutectic, which must also handle enriched lithium-6. While these two issues are well-understood and considered in the literature from the technical perspective, the
commercial perspective has been lesser considered. A final issue relates to the need for lithium-6 at a high-level of enrichment. As detailed in 7.2.3.4, the impacts of using enriched lithium-6 have not been characterised in the literature.

7.2.6. Availability, supply and use of helium

Unlike lithium-6, beryllium, and lead, the availability and supply of helium for fusion has recently been assessed by two separate studies: Clarke and Cai in (Clarke & Cai, 2012) and Bradshaw and Hamacher in (Bradshaw & Hamacher, 2013). Both studies estimate the amount of helium required for a future commercial fusion reactor and both consider helium for cryogenic cooling (i.e. liquid helium for the magnets), and helium gas for the heat transfer systems (e.g. the TBB and the divertor, see TGI #12 and TGI #6 in Table 4-4 respectively). Both studies forecast the rollout of fusion to estimate the quantities of helium required for a fusion industry and to understand the potential impact on the future helium market. Both studies suggest that helium resource for fusion is sufficient into the second half of the 21st century, but that it will become ever scarcer and more expensive. In particular, Clarke and Cai assume that the first commercial fusion reactor will begin operation in 2035; the date that ITER will now begin operations. Any delay to the fusion programme is contended by Clarke and Cai to be “unacceptable” (Clarke & Cai, 2012). Recent delays to the fusion programme, as well as the emergence of fusion start-ups mean that the demand scenarios modelled are now out of date. However, the supply-side estimates are relatively accurate due to the fact that overall resource estimates – upon which each model is predicated – have not been updated by the USGS since 2006. New data will be published later in 2020 (U.S. Geological Survey, 2020).

As such, no new assessment of helium availability and supply is necessary nor useful as the literature reflects current knowledge. However, previous results from each study can be used to provide an updated assessment model using the latest projections for demand. An updated model should explore scenarios in which the dependency on helium is reduced. For this research, an updated model provides insights into the design of an optimal commercial TBB from the perspective of helium resource.

\[206\] An important distinction must be made as regards helium as a coolant. Whilst blanket designs typically use helium gas as a coolant, for cryogenic applications, including for cooling LTS magnets, liquid helium is required. See (McDonald et al., 2002; Clarke & Glowacki, 2010). Determining the total quantity of helium required for a fusion reactor, i.e. helium liquid and gas inventories combined, is detailed in 7.4.3.3.
7.3. Research methodology

7.3.1. Research Gaps

The overarching research question (research question 3) requires an assessment of the availability, supply and use of critical resources for D-T fusion, and to understand the impact on commercial viability. With reference to this research question, the research gaps that have been identified for each of the critical TBB resources are summarised in Table 7-1.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Research gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-6</td>
<td>Whilst lithium as a resource is sufficient for the fusion industry, the challenges with supply and use of enriched lithium (lithium-6) for fusion have not been considered. Potential commercial barriers are the lack of supply chain (no current production capability), cost (of production), proliferation risks, and export control restrictions.</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Beryllium has been identified as severely limited and a long-term problem for fusion. Beryllium availability has only been explored at a high-level, i.e. overall resource base to determine the maximum capacity of fusion. Potential commercial barriers are the potential bottleneck in the beryllium supply chain (limited capability to address fusion demand), cost (of production), and the need for lithium-6 enrichment (and associated issues see above).</td>
</tr>
<tr>
<td>Lead</td>
<td>Lead resource availability and supply is not considered to be problematic for a future fusion industry. However, potential commercial barriers include limited supply chain capability for lithium-lead eutectic production (and cost), the production of long-lived radioactive isotopes such as $^{210}$Po in lead, and the need for high levels of lithium-6 enrichment (and associated issues see above).</td>
</tr>
<tr>
<td>Helium</td>
<td>Helium resource availability and supply is limited but is likely to be sufficient for the start of a commercial fusion programme. Commercial barriers remain the same as identified in previous research, specifically: overall resource availability, supply chain capability, and cost.</td>
</tr>
</tbody>
</table>

Table 7-1 Identified research gaps relating to the availability, supply and use of four critical natural resources for tritium breeding blankets.
7.3.2. Research questions

Based on the identified gaps shown in Table 7-1, secondary research questions can now be outlined to address the primary research question:

- Does the availability of each of the identified critical resources for TBBs present a barrier to the commercialisation of fusion?
- Is the supply of each of the identified critical resources for TBBs sufficient to meet the demand of the fusion industry?
- What challenges, if any, exist in the use of each of the identified critical resources from the perspective of commercialisation?
- What is the optimal design of a TBB based on the commercial issues associated with the identified critical resources?

Finally, in line with the secondary research questions detailed in the previous chapter (see 0), the difference between a route to fusion via larger fusion reactors and smaller fusion reactors\(^\text{207}\), specifically at the beginning of commercial rollout, is an additional research gap that can be usefully addressed:

- What are the differences, if any, in the use of each of the identified critical resources if pursuing routes to commercialisation based on small and large fusion reactors?

7.3.3. Research method and objectives

Each of the identified critical resources presents varying commercial challenges. The research approach must account for such differences whilst simultaneously addressing how the resources and challenges interlink. Accordingly, the methodological approach for this research will combine the methods used in Chapter 6, which adopted a forecast model and a literature-based analysis to characterise challenges with tritium and deuterium, respectively; a mixed research method and approach is adopted. Accordingly, the following objectives can be outlined:

- Develop a forecast model for the commercial rollout of fusion to project future for each of the critical resources identified.
- Using the forecast model, compare the routes to commercialisation based on both small and large fusion reactors to understand whether there are any differences regarding resource availability, supply or use

\(^{207}\) An important clarification is that “large” and “small” in this context – as in footnote 28 – refers to the power output of the fusion reactor, and not necessarily the physical size. The burn-up of lithium, lead and beryllium is assumed to be proportional to the power output of a reactor.
- Analyse the challenges identified for each of the critical resources with reference to the results of the forecast model and to literature from outside of the fusion research context
- Using the results of the research, characterise an optimal TBB from the perspective of commercial viability considering all identified critical resources.

7.3.4. Hypotheses

Finally, based on the review of the literature and the identified gaps, several hypotheses can be made:

- Broadly, the availability and supply of the identified critical resources are considered as a significant barrier that will prevent the commercial rollout of fusion compared with the ease of commercial rollout of another advanced energy technology, e.g. solar. The ramifications of which mean that substantial effort should be put into resolving or avoiding the barriers.
- Design of a commercially viable fusion blanket – which has not yet been outlined – will not align with what is considered an optimal technological blanket (i.e. a blanket that avoids or resolves technical challenges)
- Small fusion reactors will place less strain on critical resource suppliers in the early stages of commercial rollout, due to the fact that smaller reactors require less resource (which also costs less). Although both routes – via large and small reactors – will ultimately require the same amount of resource for a full commercial programme, small fusion reactors will allow resource suppliers to more gradually expand the supply capability to meet fusion demand. Accordingly, there may be substantial differences in the early stages of the commercialisation of each route.

7.4. A commercial rollout model for critical resources for tritium breeding blankets

This section describes a forecast model of TBBs resources for commercial fusion rollout.

7.4.1. Overview

It is instructive to consider the resources in terms of different blanket configurations. In the context of this research, TBB configurations can be broadly categorised by percentage lithium-6 enrichment, the choice of neutron multiplier (either beryllium or lead), and the choice of a coolant (either helium or water). This analysis will consider two types of TBB design: a beryllium-based TBB and a lead-based TBB (similar to that described in (Sánchez, 2014)). Both types can – in theory – be cooled by helium or water. As water is
considered ubiquitous and also limits the performance of a fusion reactor, only helium is considered in the model. The two types of TBB are summarised in Table 7-2.

<table>
<thead>
<tr>
<th>Blanket</th>
<th>Breeder</th>
<th>Neutron multiplier</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beryllium-based breeding blanket</td>
<td>Lithium (30% lithium-6 enrichment\textsuperscript{208})</td>
<td>Beryllium</td>
<td>Helium</td>
</tr>
<tr>
<td>Lead-based breeding blanket</td>
<td>Lithium (90% lithium-6 enrichment)</td>
<td>Lead</td>
<td>Helium</td>
</tr>
</tbody>
</table>

\textbf{Table 7-2} Conceptual tritium breeding blanket configurations for the commercial roll-out model.

Further to the two types of TBB designs, the two types of reactor must be characterised:

- A small 200 MWe reactor based on a conceptual design by Tokamak Energy, using HTS magnets
- The large 1 GWe reactor based on the EU DEMO and CFETR conceptual designs, using LTS magnets

Specification of the magnet type is relevant to this research as the helium inventory for a tokamak must also consider the amount required for cryogenic systems. It is illogical to calculate the helium demand for a TBB without considering the quantity of helium required for additional systems. By contrast, although used elsewhere in a tokamak, the quantities of lithium, beryllium and lead, are negligible compared with the requirement of helium for the cryogenic systems.

The primary reason for modelling smaller against larger reactors is to assess the quantity of resource required in the early stages of commercial roll-out. The parameters for the two reactors are detailed in Table 7-3.

\textsuperscript{208} Some beryllium-based TBBs require higher levels of enrichment.
7.4.1.1. Bias towards tokamaks

The reactors outlined in Table 7-3 suggest a bias towards tokamak-type fusion reactors. Tokamaks, as the most researched fusion reactor type, provides greater data upon which to base the model. However, while this study is based on application to the tokamak design, the results are broadly applicable to all D-T fusion reactor concepts.

7.4.2. Assumptions

7.4.2.1. Fusion reactor and resource assumptions

The following assumptions apply to both reactors:

- There is no improvement in reactor performance (i.e. power output is consistent).
- There is no reduction in the quantity of resource required per GWth over time, i.e. the model assumes no learning (e.g. see “leak learning” in (Clarke & Cai, 2012)).
- Required quantities of lithium-6, beryllium and lead resource are dependent on the rated fusion power (per GWth), i.e. there are zero scaling effects in the resource required for a small and large reactor\(^{210,211}\).
- However, scaling effects for helium in fusion reactors is factored in per previous analysis of experimental results (Clarke & Cai, 2012).

\(^{209}\) Assumes blanket operating temperatures are high enough to achieve 42% efficiency.

\(^{210}\) Data for scaling effects for future breeding blankets not available due to no experiments having yet taken place, unlike helium coolant tests.

\(^{211}\) For example, the total resource required for a grid of 100 GWe installed capacity is the same for both small and large reactors, but 5 times the number of smaller reactors are needed than large.
- Annual burn-up of lithium, beryllium and lead are considered. Defining the capacity factor of the reactor is necessary to calculate nominal burn-up (see (Bradshaw, Hamacher & Fischer, 2011)). Accordingly, the reactor is assumed to operate at 100% capacity factor, i.e. it is continuously operating, with no maintenance or downtime, with a 40-year lifetime. The projections are thus optimistic, providing the best-case scenario\(^{212}\).

- Leakage of helium and required top-up is also considered (see 7.4.3.3.3).

- The quantity of available natural resource, in particular the total resource base for beryllium, is assumed to remain constant from the current date (2020) until the start of the model (2035), i.e. demand for lithium-6, beryllium, lead or helium from other industries is not considered:
  - Lithium and lead resource are ample and thus considered negligible.
  - Resource base estimates for beryllium vary, and the quantity of beryllium that might be supplied between 2020 and 2035 is assumed negligible.
  - For helium, forecasts are made based on previous data by (Cai et al., 2010), i.e. no additional supply or demand from 2010 to 2035

- Recycling is not considered. By 2080 – after a 40-year lifetime – the quantity of resource that could be recycled from the first reactors will be negligible compared with demand from the future fusion industry which, by that time, is installing hundreds of GWe per year.

- The quantity of resource per GWth for each reactor is estimated via a parametric analysis of previous designs, or single studies where limited data is available. The blanket designs are, therefore, a theoretical amalgamation of existing designs. Input data for each resource is detailed in 7.4.3.

7.4.2.2. Commercial roll-out assumptions

The model for the commercial roll-out of the two D-T fusion reactors in Table 7-3 follows assumptions from (Clarke & Cai, 2012; Lopes Cardozo, Lange & Kramer, 2016). In particular, the study by Lopes-Cardozo which the historical doubling rate for fission, solar, and wind technology in order to account for the scale-up of a new industry, supply chains, and market uptake of new technology was used to determine the growth rate for fusion (see Figure 7-9). The rollout of fusion reactors after the start date of the model assumes reactors are deployed at an exponential rate with a doubling period of 3 years\(^{213}\), per (Lopes

\(^{212}\) Reactor operation is unlikely to be continuous. Downtime will be needed for maintenance, for instance.

\(^{213}\) 1000 large reactors per doubling period; 5000 small reactors per doubling period.
Cardozo, Lange & Kramer, 2016), i.e. the first reactor is built in 2035, two reactors are built by 2038, four reactors are built by 2041 etc. When the number of reactors being built per doubling period reaches 1000 GWe (corresponding to 1000 large reactors or 5000 small reactors), the rate at which they are built continues at a rate of 1000 GWe per doubling period. This is assumed to reflect the best-case scenario; anything faster would require unprecedented growth beyond historical rates in the advanced energy sector.  

Figure 7-9   **Historical data for the commercial roll-out of solar, wind and fission technology, reproduced with permission from** (Lopes Cardozo, Lange & Kramer, 2016).

The model assumes that development is successfully accelerated and the first commercial fusion reactor (FOAK) is built in 2035 (for both large and small fusion reactors). However, in assuming that resource requirements stay the same between the current time and the start of the model, the start date of the model is largely ineffectual. In reality, delays to the start of a fusion programme will impact greatly on the amount of helium available in particular – as detailed in (Clarke & Cai, 2012). However, without dynamic modelling, it is unproductive to consider the delay. This is considered as a limitation of the model.

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214 The rate of commercial deployment of fusion technology would have to achieve unprecedented levels to achieve the current climate change goals, as discussed in (Lopes Cardozo, Lange & Kramer, 2016; Lopes-Cardozo, 2019).
Finally, the model assumes fusion reactors for the generation of electricity only. Projections by the IEA suggest that the world electricity generating grid will be around 13 TW by 2050, see (International Energy Agency, 2017). The model assumes that global electricity demand will remain stable and that the grid capacity from 2060 is fixed at 13 TW. Therefore, 5 TW represents approximately a 40% share of total installed energy generating capacity – which is used as a benchmark and for context to show the contribution of fusion to global electricity generation. The model only considers fusion for electricity generation, which is a key limitation discussed further in 7.5.6.3.

7.4.3. Critical resources: input data

As beryllium- and lead-based TBBs require different levels of lithium-6 enrichment and different overall quantities of lithium, for the purposes of the model the analysis separates the two neutron multipliers into two separate cases, with lithium-6 modelled for both.

7.4.3.1. Beryllium-based blankets: beryllium and lithium-6

The amount of beryllium per GWth was estimated via analysis of beryllium-based blanket concepts as shown in Table 7-4. The average mass of beryllium per GWth is estimated at 109 tonnes per GWth. Beryllium burn-up is estimated at 0.22 tonnes per GWth per year (Maisonnier et al., 2005). The initial load of beryllium is expected to last 40 years, and it is topped-up with new beryllium in-situ to replace the burnt-up beryllium (optimistic). Beryllium required for other fusion reactor components, e.g. first wall, is not considered.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Beryllium (tonnes per reactor)</th>
<th>Rated power (GWth)</th>
<th>Beryllium (tonnes per GWth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karlsruhe Beryllium Handling Facility (KBHF) estimate</td>
<td>400</td>
<td>2.7</td>
<td>148</td>
</tr>
<tr>
<td>(Personal communication with Aniceto Goraieb, Karlsruhe Beryllium Handling Facility, Germany, and Christopher Dorn, Beryllium4Fusion)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>European Power Plant Conceptual Study (PPCS) (average of (Maisonnier et al., 2005; Fischer, Pereslavtsev &amp; Hermsmeyer, 2005))</td>
<td>500</td>
<td>3.6</td>
<td>139</td>
</tr>
<tr>
<td>MIT (Commonwealth Fusion Systems) ARC reactor 215 (Sorbom et al., 2015)</td>
<td>91</td>
<td>0.525</td>
<td>173</td>
</tr>
<tr>
<td>Steady-state Tokamak Reactor (Tokimatsu et al., 2003)</td>
<td>110</td>
<td>3</td>
<td>37</td>
</tr>
<tr>
<td>EU DEMO helium-cooled pebble bed (HCPB) (Fischer et al., 2009)</td>
<td>120</td>
<td>2.53</td>
<td>47</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>109</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 7-4**  
Data from conceptual reactor designs to estimate beryllium demand.

The amount of lithium-6 as suggested by Tokimatsu et al. is 97 tonnes of natural lithium per reactor (for a 3 GWth reactor), so if assuming enrichment of 30%, this indicates 9.7 tonnes lithium-6 required per GWth (Tokimatsu et al., 2003). However, as no lithium-6 enrichment level is provided by Tokimatsu et al., the initial load is taken from (Bradshaw, Hamacher & Fischer, 2011; Maisonnier et al., 2005) as 1.5 tonnes per GWth (for 30% enrichment), shown in Table 7-5.

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215 The ARC concept adopts a molten salt “FLiBe” blanket (Sorbom et al., 2015). Whilst not a solid beryllium-based TBB concept, it is included in the analysis as molten salts TBBs are actively being pursued as a viable option, and thus the ARC concept provides a useful data point for the projection of fusion beryllium demand.
## 7.4.3.2. Lead-based blankets: lead and lithium-6

A review of existing lead-based TBB designs – see (Li Puma et al., 2006; Sardain et al., 2006; Abdou et al., 2015; Maisonnier et al., 2005) – concluded that the best available data is that used in the previous resource study by Bradshaw et al., which is based on the EU DEMO concept, see (Bradshaw, Hamacher & Fischer, 2011; Maisonnier et al., 2005). The data for the lead-based TBB is shown in Table 7-6. The enrichment of lithium-6 is 90%.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Tonnes per GWth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead initial blanket load</td>
<td>1715</td>
</tr>
<tr>
<td>Lead burn-up per year (top-up required)</td>
<td>1.30</td>
</tr>
<tr>
<td>Lithium-6 initial load</td>
<td>11.8</td>
</tr>
<tr>
<td>Lithium-6 burn-up per year (top-up required)</td>
<td>0.12</td>
</tr>
</tbody>
</table>

*Table 7-6 Estimated requirement for lead and lithium-6 for lead-based tritium breeding blankets, from (Bradshaw, Hamacher & Fischer, 2011; Maisonnier et al., 2005).*

## 7.4.3.3. Helium for beryllium- and lead-based blankets

### 7.4.3.3.1. Hydrogen as an alternative coolant for all fusion reactor systems

Helium is a resource critical for other systems in a fusion reactor beyond the TBB. As such, in order to accurately assess the amount of helium required for fusion, the helium required for the whole reactor must be modelled not just the helium required for the blanket. HTS magnet technology can produce high fields and current densities whilst operating at higher temperatures than LTS. HTS magnets cooled to 20 K could still produce the necessary critical current density and thus, as indicated in Figure 7-10, could be cooled by a cooling medium other than helium.
Indirect hydrogen (iLH$_2$) cooling systems use a helium gas exchanger with a hydrogen bath at 20 K in which the cooling power is transferred from the hydrogen bath, as shown in Figure 7-11.

Although some systems still require cooling to liquid hydrogen temperatures, e.g. the cryopump and for pellet injection (see TGI #4 in Table 4-4), an iLH$_2$ system could be used to cool the magnets on an HTS tokamak as well as the heat transfer systems, i.e. the TBB and divertor, as shown in Figure 7-12. As such, iLH$_2$ cooling may reduce the quantity of helium resource required (Clarke & Glowacki, 2010; Glowacki et al., 2015).
Accordingly, iLH$_2$ is only possible on tokamaks using HTS magnets, as indirect hydrogen cooling can only cool to $\sim$20 K. If using LTS magnets, iLH$_2$ would not be viable as it is not possible to cool to temperatures required for them to function using iLH$_2$. For blanket systems, however, iLH$_2$ could be used with a helium gas coolant system, which would reduce the helium inventory required for blanket cooling as helium would only be required for the primary loop in the blanket, and the cooling could be performed by liquid hydrogen.

For this research, it assumed that the HTS magnets are cooled by iLH$_2$ only, using the estimate by Clarke and Cai that iLH$_2$ for HTS magnets would reduce the required cryogenic inventory by 50% (Clarke & Cai, 2012). The large tokamak uses LTS magnets cooled by helium (at 4.2 K), for comparison$^{216}$. 

7.4.3.3.2. Helium input data for the model

Bradshaw et al. suggest that the total inventory of helium required for a fusion reactor is 25 tonnes per GWth (Bradshaw & Hamacher, 2013). The quantity is split between the heat transfer systems and the cryogenic systems. 9.6 tonnes of helium are required for the heat transfer systems – with 85% of that quantity for blanket systems – and 14.2 tonnes of helium are for the cryogenic systems. Clarke and Cai suggest the total inventory of helium required for a fusion reactor is 50 tonnes per GWth (Clarke & Cai, 2012). The analysis by Bradshaw

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$^{216}$ A separate case in which HTS magnets are assumed to require the same inventory of helium, i.e. no 50% saving on inventory, is also modelled to understand scaling effects in small reactors, see 7.4.3.3.3.
and Hamacher is considered to be less accurate than that of Clarke and Cai, as the latter estimate the helium quantities based on the historical use of helium in fusion reactors (using experience from JET and the design basis of ITER). As such, for this study, Eq. 7.5 and 7.6 from (Clarke & Cai, 2012) are used to calculate the helium inventories for cryogenic and heat transfer, respectively.

\[
\text{Eq 7.5} \quad I_{\text{cryo}} = 0.048 \cdot Q_{\text{th}}^{0.75} \text{ MMscf}^{217} \\
\text{Eq 7.6} \quad I_{\text{HT}} = 0.015 \cdot Q_{\text{th}}^{0.75} \text{ MMscf}
\]

Where \( I_{\text{cryo}} \) is the cryogenic system required for magnet cooling, cryopumps, pellet injection, RF, NBI, ECRH, tritium plant, all of which require a helium cryopump, and where \( I_{\text{HT}} \) is the cryogenic inventory required for the heat transfer systems only (divertor and blanket). \( Q_{\text{th}} \) is the thermal power of the reactor. 0.048 and 0.015 are constants mathematically derived from the cryogenic inventories for JET and ITER (Clarke & Cai, 2012). As such, the formulae result in inventory estimates that scale non-linearly with device size.

### 7.4.3.3.3. Comparing small tokamaks with HTS magnets against large tokamaks with LTS magnets

The use of HTS is assumed to reduce the required helium inventory by half versus LTS. The HTS magnets are assumed to be cooled by liquid hydrogen via an iLH\(_2\) cooling system. The quantity of helium required for all other systems is assumed to remain constant. The inventories for the two reactors modelled in this research are shown below

- **Large (LTS) reactor:**
  \[ I_{\text{cryo}} = 76.7 \text{ tonnes}; \ I_{\text{HT}} = 23.6 \text{ tonnes}; \ I_{\text{total}} = 100.3 \text{ tonnes (21.4 MMscf)} \]

- **Small (HTS) reactor:**
  \[ I_{\text{cryo}} = 11.8 \text{ tonnes}; \ I_{\text{HT}} = 7.3 \text{ tonnes}; \ I_{\text{total}} = 19.1 \text{ tonnes (4.1 MMscf)} \]

Leakage is considered at 7% per year for the cryogenic system and at 18% per year for the heat transfer system, per (Clarke & Cai, 2012). It is assumed that no learning to decrease these losses occurs. Further, the helium produced as a fission product from the fission of lithium or beryllium, as well as the helium ash from the D-T fusion reaction itself are considered negligible and do not top-up the helium inventory.

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\(^{217}\) Both tonnes and MMscf are used as units in the literature, where 1 tonne = 0.2133 MMscf.
7.4.3.4. **Summary of resources**

The total quantities of resource required for beryllium-based for both large and small reactors are provided in Table 7-7 and for lead-based blankets in Table 7-8.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Function</th>
<th>Quantity (tonnes) large reactor</th>
<th>Quantity (tonnes) small reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-6</td>
<td>Initial blanket load</td>
<td>3.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Blanket burn-up (top-up required) per year</td>
<td>0.29</td>
<td>0.1</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Initial blanket load</td>
<td>260</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Blanket burn-up (top-up required) per year</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Helium</td>
<td>Initial load (all systems)</td>
<td>100.3 (21.4 MMscf)</td>
<td>19.1 (4.08 MMscf)</td>
</tr>
<tr>
<td></td>
<td>top-up required per year (all systems)</td>
<td>9.9 (2.1 MMscf)</td>
<td>2.2 (0.47 MMscf)</td>
</tr>
</tbody>
</table>

*Table 7-7*  **Resources required for beryllium-based tritium breeding blankets (lithium-6, beryllium and helium).**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Function</th>
<th>Quantity (tonnes) large reactor</th>
<th>Quantity (tonnes) small reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-6</td>
<td>Initial blanket load</td>
<td>25</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td>Blanket burn-up (top-up required) per year</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Lead</td>
<td>Initial blanket load</td>
<td>4092</td>
<td>857.9</td>
</tr>
<tr>
<td></td>
<td>Blanket burn-up (top-up required) per year</td>
<td>3.1</td>
<td>0.65</td>
</tr>
<tr>
<td>Helium</td>
<td>Initial load (all systems)</td>
<td>100.3 (21.4 MMscf)</td>
<td>19.1 (4.08 MMscf)</td>
</tr>
<tr>
<td></td>
<td>top-up required per year (all systems)</td>
<td>9.9 (2.1 MMscf)</td>
<td>2.2 (0.47 MMscf)</td>
</tr>
</tbody>
</table>

*Table 7-8*  **Resources required for lead-based tritium breeding blankets (lithium-6, lead and helium).**

Helium required for both blanket types is assumed the same. However, the small tokamak using HTS is assumed to have half the cryogenic inventory. A separate case is included in which smaller tokamaks using HTS are cooled solely by helium, which is shown separately in Table 7-9.
<table>
<thead>
<tr>
<th>Resource</th>
<th>Need</th>
<th>Quantity (tonnes)</th>
<th>Resource</th>
<th>Need</th>
<th>Quantity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>Initial load (without Heat Transfer systems)</td>
<td>76.7 (16.4 MMscf)</td>
<td>Helium</td>
<td>Initial load (without Heat Transfer systems)</td>
<td>11.8 (2.5 MMscf)</td>
</tr>
<tr>
<td></td>
<td>top-up required per year (without Heat Transfer systems)</td>
<td>5.5 (1.2 MMscf)</td>
<td></td>
<td>top-up required per year (without Heat Transfer systems)</td>
<td>0.9 (0.2 MMscf)</td>
</tr>
</tbody>
</table>

Table 7-9  Helium required only for cryogenic systems (e.g. magnet, cryopump).

7.5. Results, Analysis and Discussion

In this section, the results of the model are analysed and discussed with each resource addressed in sequence.

7.5.1. On the use of lithium-6 in tritium breeding blankets

7.5.1.1. Results

![Figure 7-13 Lithium-6 required for beryllium-based blankets based on small fusion reactors (200 MWe).](image-url)
7.5.1.2. **Availability and supply of lithium-6**

A total of roughly 400 tonnes of lithium-6 will be required for the first 100 GWe and the first 25 GWe of fusion reactors using beryllium-based blankets and lead-based blankets respectively. This quantity is roughly the amount produced by the U.S. over a decade using the COLEX process (U.S. Department of Energy, n.d.). At maturity (from 2075), lithium-6 requirements to sustain a fusion industry are 1500 tonnes per year and 9000 tonnes per year for beryllium-based and lead-based blankets, respectively.

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218 Lithium-6 resource requirements are the same per GWth, thus when the industry reaches maturity absolute resource requirements are the same irrespective of reactor size. The impact of reactor size on resource requirements in the early stages of commercial deployment is discussed in 7.5.5.
Whilst the initial quantities of lithium-6 have been produced before, and over shorter timescales, meaning that this may represent a manageable quantity to produce again, the COLEX process is not favourable, and perhaps the production of lithium-6 is altogether unfavourable. Firstly, the viability of developing facilities to produce lithium-6 will be assessed for commercial viability, with cost estimates included. Thereafter, potential challenges relating to proliferation with the use of lithium-6 as a resource for fusion are discussed.

7.5.1.3. Lithium-6 enrichment for fusion

Any fusion programme aiming for commercial fusion on an accelerated timescale will need to produce lithium-6 at low-cost and ahead of any plan to deploy a FOAK. Effectively, therefore, the lithium-6 problem presents a potential bottleneck for commercialisation. Firstly, lithium-6 enrichment facilities would need to be set up to support the fusion industry. The COLEX process is the only historically proven way to produce lithium-6 at scale. The site at Oak Ridge National Laboratory, dubbed Y12, does not exist anymore, and the costs of its operation were unknown. What is known, however, is that the process is complex, energy-intensive and can be environmentally damaging (Brooks & Southworth, 2011; Ault et al., 2012; Giegerich et al., 2019). As such, the COLEX process is not considered a viable option for the production of lithium-6 for a fusion programme. The issue has recently been recognised Giegerich et al.219, who suggest that "unavailability of lithium enrichment facilities that could meet DEMO requirements is a threat to the success of fusion" (Giegerich et al., 2019). Further to this recent study, however, a previous review of lithium separation processes was carried out to assess the production of isotopically lithium-7 rather than lithium-6 for the fission industry220 (Ault et al., 2012). There are two key conclusions of these studies that are relevant for this research.

Ault et al. suggest that whilst there are several processes to produce enriched lithium, laser enrichment processes (using the AVLIS process whereby the energy of lasers are altered to selectively ionise lithium isotopes) are unsuitable due to the fact that it is a controlled technology. It is controlled because with technical modifications AVLIS processes can be adapted to instead enrich uranium (Ault et al., 2012). Noting this limitation, Giegerich et al. sought to develop a new process based on the established COLEX process, but which eliminates technical and environmental difficulties. A new process dubbed ICOMAX (Improved Column-based Mercury Amalgam eXchange) has been developed and

219 Refer to footnote 199.

220 Interestingly, this study was focused on reducing tritium production in fission reactors, rather than producing tritium for fusion.
demonstrated at low TRL, see (Giegerich et al., 2019). It is suggested that several decades of R&D are required for the technology to be scaled-up, and the cost of production via the ICOMAX process is as yet unknown. The two issues outlined in these studies; the potential for proliferation and the cost and time to develop lithium-6 technology must be explored in the context of this research, i.e. the potential limitation they place on the use of lithium-6 for commercial fusion. The latter is discussed first.

7.5.1.4. Cost of commercial production of lithium-6

The market price for natural lithium (lithium carbonate) is not useful as an indicator for the production of lithium-6, as natural lithium as a feedstock is of negligible cost. Rhinehammer and Wittenberg estimate the cost of lithium-6 via the COLEX process between US$ 600/kg and US$ 1250/kg in 1978$ (US$ 2350 to US$ 4900 in 2019$) (Rhinehammer & Wittenberg, 1978). More recently, von Hippel et al. estimate lithium-6 to cost US$ 3000/kg in 2005$ (US$ 4000/kg in 2019$) (Von Hippel et al., 2012). At a nominal cost of US$ 4500 per kg (US$ 4.5 M per tonne), the lifetime cost of lithium-6 for a 1 GWe reactor is US$ 69 M for a beryllium-based TBB and US$ 165 M for a lead-based TBB. It is unknown whether von Hippel et al.’s cost estimates account for potential regulatory, export or other supply chain costs. Given the complexity of factoring for such costs, these estimates such should be considered as conservative.

Although developed for lithium-7 enrichment – and for a crown ether process (down-selected as the optimal method in that study) – Ault et al.’s study provides indicative cost estimates for lithium enrichment facilities (Ault et al., 2012). The capital cost of an enrichment plant is estimated at US$ 400 M in 2012$ (US$ 445M in 2019$) with annual operating costs at US$ 75 M in 2012$ (US$ 84 M in 2019$) for a 400 tonne per year production capacity. This capacity would be sufficient for the start of a commercial fusion programme221; enough to support 500 GWe and 125 GWe installed capacity for reactors with beryllium-based and lead-based blankets respectively. The extent to which the capital cost and operational costs of lithium-6 production were considered in the lithium-6 cost estimates in (Rhinehammer & Wittenberg, 1978; Von Hippel et al., 2012) is unknown. They are thus included here to highlight that such costs must be considered in projections, where previously they have been ignored (Tokimatsu et al., 2003; Ward, 2007; Bradshaw,

221 Ault et al. suggest that the higher purity lithium-7 is more expensive to produce due to the number of stages of enrichment needed. This suggests that lithium-6 enrichment, which does not need to be enriched to high purity, could be produced at lower cost than Ault's estimates for lithium-7 (Ault et al., 2012). It also suggests that the cost of lithium-6 enrichment to 30% is likely to be lower than enrichment to 90%.
Hamacher & Fischer, 2011). Finally, to support a fusion industry that delivers more than 30% of global electricity production, annual production capacity would need to be in the order of 2,000 to 10,000 tonnes per year, for beryllium-based and lead-based TBBs respectively.

7.5.1.5. Lithium-6 and proliferation

Lithium enriched in lithium-6 beyond natural levels, like deuterium, is a controlled isotope subject to export control regulations. Together, deuterium and lithium-6 constitute the two parts of the lithium deuteride target materials required to create a thermonuclear weapon. Lithium enriched beyond natural levels as well as separation facilities, plants and equipment is restricted under export control (Canadian Nuclear Safety Commission, 2000; International Atomic Energy Agency (IAEA), 2019; British Government, 2012). This may also place regulatory constraints, and additional costs, in developing the lithium-6 production facilities detailed in 7.5.1.4.

For the widespread rollout of fusion across the world, export control of lithium-6, and the potential for proliferation from a key fusion fuel could be limiting. Moreover, the level of enrichment nor the quantity may not be important – but it might instead be that any level of enrichment is problematic, i.e. production of lithium-6 altogether. The potential for technology to produce lithium-6 alongside deuterium to nations or organisations wishing to develop a fusion programme may present them with a pathway to a thermonuclear weapon. From the perspective of nuclear regulation, domestic and international, the problems associated with lithium-6 production for fusion may present rationale to adopt a more stringent regulatory framework for fusion to monitor lithium-6 (and deuterium) production, i.e. establish a safeguarding regime. If this transpires, however, it may be difficult to export, e.g. a commercial fusion reactor originating in the UK to anywhere in the world that is, for instance, not a party to the Nuclear NPT. This concern over the use of lithium-6 is a significant omission in otherwise comprehensive analyses of the proliferation potential of fusion in (Goldston, Glaser & Ross, 2009; Englert, Balloni & Liebert, 2010).

Like the previous analysis on deuterium supply (6.2.5), this analysis is the first consideration of potential regulatory issues with the use of lithium-6 for fusion. The findings of this

222 If a plant were set up for co-production of lithium-6 and lithium-7 the cost of each will come down, each serving individual markets. Note that the depleted lithium (known as “tails”) from the enrichment process, could be sold for on the lithium-7 market, e.g. for use in advanced fission reactors. The future advanced fission and fusion could thus share the development of a lithium enrichment process where tritium avoidance and tritium production are the respective goals.
research into the potential for fusion proliferation in the supply and use of resources necessitates further exploration, probably by regulatory bodies.

7.5.1.6. **Lithium-6: A way forward**

Where deuterium can easily be supplied in relatively small quantities, lithium-6 is required in significantly larger quantities. Ostensibly, the supply of lithium-6 appears more problematic than the supply of deuterium. Furthermore, from a technical perspective, providing deuterium for fusion is an unavoidable problem. Fusion reactors operating on all core fuel cycles: D-T, D-D and D-He3 (but not proton-Boron-11), require deuterium; it is essential. Tritium, on the other hand, can be produced without lithium enrichment, but it is more technically challenging. On the other hand, if shipped as fully fabricated TBB modules, with no feasible way to extract lithium-6, the issues associated with the potential proliferation of lithium-6 enrichment technology may be avoided. However, this would still prohibit fusion from being a globally deployable energy source, as the supply chain capability would reside in the hands of only select nations.

Despite potential challenges, there are three primary means to avoid the proliferation concerns associated with the use of lithium-6 for nuclear fusion:

1. Produce lithium-6 only in nations with appropriate infrastructure, i.e. existing nuclear power nations, and export lithium as a blanket product as part of the system, without providing the supply chain
2. Develop fusion reactors to create commercial products and do not develop fusion for electricity generation. For example, fusion could be used for the production of hydrogen, ammonia or for medical isotopes, which could then be exported, with a stable nation operating the facilities required to produce lithium-6.
3. Perhaps the most technically challenging but commercially favourable solution is to avoid the use of enriched lithium altogether. The use of natural lithium for fusion has none of the restrictions associated with the use of lithium-6.

Options 1 and 2 may limit the global deployment of fusion. Therefore, it is concluded the optimal solution to the lithium-6 problem is to develop natural lithium blankets for the commercial fusion programme to be successful (option 3). This might represent a significant technical challenge, but commercially it provides a much faster route to fusion.
7.5.2. On the use of beryllium in tritium breeding blankets

7.5.2.1. Results

**Figure 7-16** Beryllium required for small fusion reactors against resource estimates (with installed electricity generating capacity shown for context).

**Figure 7-17** Beryllium required for large fusion reactors against resource estimates (with installed electricity generating capacity shown for context).
7.5.2.2. **Long-term availability of beryllium**

Hypothetically, if all the world’s fusion reactors depended on beryllium-based blankets, the resources for fusion could not be considered sustainable as around 2 million tonnes would be required for 5000 GWe (~40%) of installed capacity, well over even the highest resource base estimates. Notwithstanding other non-fusion beryllium demand (which may reduce the quantity available but might also spur exploration of new resource\textsuperscript{223}), the world’s identified beryllium resources are capable of supplying only 400 GWe installed capacity of fusion reactors with beryllium-based TBBs (requiring ~112,000 tonnes of beryllium)\textsuperscript{224}. This number of reactors is approximately the same as the installed capacity of fission reactors globally (2019). As such, before or at this point, fusion reactors must use lead-based blankets or find a solution to reduce beryllium content significantly. Recycling of spent beryllium from early fusion reactors cannot solve the problem as the first reactors at the end of life make up only a very small fraction of new reactors required. Further, the cost of recycling would need to be reduced in order for it to be competitive with newly mined resource. Indeed, if the scarcity of beryllium resource drives an increase in the price of mined beryllium, the cost of recycling may become competitive\textsuperscript{225}.

The reduction of beryllium content in fusion blankets is explored in (Kolbasov, Khripunov & Biryukov, 2016; Ma \textit{et al.}, 2014). Shimwell \textit{et al.} detail a conceptual TBB design with a 10% reduction in beryllium versus existing designs without significantly reducing TBR (Shimwell \textit{et al.}, 2016). However, such a reduction is not substantial enough to resolve the issue. The first 70 GWe of fusion plants will use up the entirety of Materion’s Spor Mountain mine (see 7.2.4), albeit that – according to the projections in the rollout model – this would happen over a 30 to 35 year period, with demand increasing at a steady rate.

7.5.2.3. **Future beryllium supply for fusion**

After Spor Mountain is depleted, new mines and facilities will have to be commissioned (sometime around 2060, based on the projections of this model). As such, if assuming that the resource base is higher than 100,000 tonnes (see (Dombrowski, 1997)), then it is the capacity of the supply chain that becomes the limiting factor. If requesting large quantities

\textsuperscript{223} The beryllium market anticipates demand to be as high as 450 tonnes per year by 2030 (U.S. Geological Survey, 2019a).

\textsuperscript{224} For reference, 1600 GWe installed capacity represents roughly 10% of global electricity generation.

\textsuperscript{225} Up to 25% of beryllium consumption is from recycled beryllium (U.S. Geological Survey, 2019a).
of beryllium (hundreds of tonnes) in short lead-time will put a strain on supply capability. The beryllium industry is capable of matching small increases in demand (∼400 tonnes per year), but any substantial increase (in the order of ∼1000 tonnes per year) will require an upgrade to the existing infrastructure and the supply chain. In the near-term, beryllium could be purchased in smaller quantities and stockpiled. Indeed, this is already done for the distinctly different reason that beryllium is a strategic material, which is discussed subsequently in 7.5.2.4. However, this does not solve the longer-term supply problem. To increase mine and process capacity will require time and investment. Materion suggest a lead time of 7 to 10 years would be required to assess viability, secure financing, assess environmental impacts, seek regulatory permits, and build necessary supply chain infrastructure, including for (e.g. railways, ports, etc.) (Trueman & Sabey, 2014; Personal communication with Steven Freeman and Phillip Sabey of Materion Corporation, U.S.).

The beryllium market can respond to increased demand by increasing the price of beryllium, which may prompt new exploration for minable beryllium deposits. If the cost of mining remains the same, but the demand increases substantially then the beryllium industry will necessarily increase its prices to quell demand until it has the capability to match the new demand, see (Humphreys, 2014). Increased prices for beryllium may permit the conversion of what were formerly economically unviable resources into minable reserves226. It may also promote exploration, substitution and recycling227. However, long-term contracts would be required to provide a guarantee that the initial capital investment from the newly mined deposit could be recovered (Humphreys, 2014). This cost is likely to be footed by the fusion industry. Further resources may then become available. However, as beryllium is scarce on Earth, and currently, there is minimal demand, the fusion industry would instantly become the largest customer for the beryllium industry. In this scenario, the beryllium-fusion industry would become co-dependent; and would be monopolistic and monopsonistic, representing a risk for both industries. The beryllium industry scales-up to supply almost exclusively to one customer, and the fusion industry is beholden to the price set by the beryllium industry.

The economics and dynamics of resource supply and demand for finite natural resources are well understood228. Geological availability, or lack of, does not automatically imply

226 The beryllium price has been increasing in recent years and it may increase further as a result of impending fusion demand.

227 Beryllium recycling is currently 20-25% of consumption. As an expensive material, applications that can avoid using beryllium have already made the switch away from beryllium.

228 For interest, refer to “Limits to growth” by the Club of Rome.
market availability; indeed, physical availability in the ground is rarely, if ever, a constraint on mineral supply (Wellmer et al., 2018). Conventional commodity markets are made up of numerous buyers and sellers in which the convention is that no one has sufficient market power to be price makers; everyone is a price taker. Price is determined by the dynamics of supply and demand (see (Hubbert, 1962; Sterman, 2000)). However, in view of future fusion demand and scarcity of beryllium, noting that beryllium is currently traded via private contracts, the beryllium market will likely not be conventional. The emergence of fusion as a customer requiring significantly larger quantities of beryllium than is produced in the current market brings risk. Recent restrictions on exporting resources for renewable energy have demonstrated how new energy technology can result in new dependencies, for which the dynamics and forces in the system can be just as problematic as the existing market for oil (Wellmer et al., 2018; Naill, 1992). Guarantees will be required for the beryllium industry if it is to proceed with scaling up; it needs the certainty that it is scaling up to support an industry that will succeed. The fusion industry is unlikely to be able to provide this in the near-term as it is in its infancy and is unproven both technologically and in the market. A shortage of sought-after commodity serves to push prices up and stimulate companies to invest in new production capacity, but a surfeit of supply leads to a fall in price and curtailment of output (Humphreys, 2014). If the beryllium industry ramped up supply chain and fusion as a commercial endeavour was not successful, it could crash the beryllium market. Similarly, with a monopoly over the market, the beryllium industry can exercise power in choosing market prices that the fusion industry would have to accept. It is likely that the beryllium industry would view fusion as too speculative a business risk to undertake without government guarantees, and it is likely that to avoid price-setting that government would need to be involved from the perspective of the fusion industry.

7.5.2.4. Beryllium as a strategic material

The U.S. controls the majority of global beryllium supply. Interestingly, U.S. TBB designs are predominantly lead-based. Whilst this may suggest a realisation about the availability (and cost) of beryllium, there may be a strategic rationale, too. Beryllium is listed as a strategic material. Strategic materials are critical for maintaining the capability to produce certain industrial goods or ensuring that a nation has the means to defend itself (Humphreys, 2014). The scaling up of beryllium supply, as well as the threat of resource exhaustion, may be driven to an extent by geopolitical considerations. The U.S. may have concerns over the widespread production, distribution and exhaustion of beryllium resource. As it already does today (see (Boland, 2012)), the U.S. may exercise control over any increased demand from the fusion industry.

A secondary, related concern is that China and Russia conceal their resource base estimates and production levels, and the U.S. does not fully disclose its resource base
estimates (Personal communication with Keith Smith of Materion Corporation, U.S.). Relatedly, therefore, even if estimates are grossly incorrect and the physical availability of beryllium is not a limitation, the geographic concentration may be an issue (Humphreys, 2014; Wellmer et al., 2018).

The analysis of beryllium as a strategic material requires further exploration in the fusion context, including from a strategic perspective, with support from regulatory and security authorities.

7.5.2.5. Cost

Based on this assessment, using the price of beryllium at US$ 630,000 per tonne (2017$), the cost of beryllium resource only is estimated at ~US$ 34 M for a 200 MWe and ~US$ 163 M for a large 1 GWe reactor. It is suggested that a roughly ten-fold increase in cost will apply for the processing of beryllium from its initial composition as beryllium oxide (Personal communication with Aniceto Goraieb, Karlsruhe Beryllium Handling Facility (KBHF), Germany, and Christopher Dorn, Beryllium4Fusion). This is because beryllium is difficult to manufacture. Beryllium processing facilities for fusion applications are currently only at laboratory-scale – e.g. at KBHF in Germany – and a specific grade of beryllium must be used specifically for fusion application. Materion has developed a grade of beryllium, S-65, which has superior crack resistance under high heat cycling (Dombrowski, 1997). It also has low uranium impurity, as even very small quantities of uranium can yield significant quantities of plutonium in the blanket, presenting an alternative, more significant, proliferation risk, see (Kolbasov, Khripunov & Biryukov, 2016). Thereafter, this grade of beryllium must further be processed into a format (e.g. beryllide pebbles) suitable for a TBB. As such, the cost of processed beryllium for the blanket alone could be around $1.6 B per GWe. While it is not in the scope of this thesis to provide a full assessment of cost, such a TBB for a commercial fusion reactor may render it uneconomical. Further, this challenges the convention that the cost of blanket materials is negligible, as detailed in (Ward, 2007; Sagara et al., 2000; Tokimatsu et al., 2003). Similarly, while lithium-6 enrichment for beryllium-based TBBs is lower than for lead-based TBBs, the cost is not zero. At an estimated US$ 4000/kg, the lithium-6 cost for a beryllium-based TBB is US$ 3 M and US$ 14.4 M for a 200 MWe and 1 GWe reactor respectively. Whilst negligible compared with the cost of beryllium (see 7.5.2.5), other challenges in the supply of lithium-6 may drive up this cost.

Finally, next-step DEMO reactors are not due to be commissioned until 2055, and a FOAK likely a decade or more thereafter. Such a delay – noting that the model here assumes the commercial programme will start in 2035 – would likely also impact the availability of beryllium. 20 years of beryllium supply at 200 to 300 tonnes per year is 5,000 tonnes (one-
quarter of Spor Mountain, UT reserves). Thus, unless new deposits are identified, then delays to the fusion programme may further limit the quantities of beryllium available.

7.5.2.6. **A way forward for the use of beryllium in tritium breeding blankets**

Even if actual beryllium resources are an order of magnitude larger than current estimates, beryllium for fusion is still potentially problematic long-term for strategic and cost concerns. In the short-term, the availability is also problematic due to the capability of the beryllium industry’s capability and its supply chain. It is concluded that it might be plausible for beryllium to support the first generation of fusion reactors, e.g. the first 100 GWe, requiring around 30,000 tonnes beryllium, with subsequent generations transitioning to other TBBs or away from D-T fusion:

- Generation 1: Beryllium-based TBBs
- Generation 2: Transition to alternative TBB design which is not dependent on beryllium, or to advanced (e.g. D-D) fusion fuel cycle

Avoiding the use of significant quantities of beryllium for fusion reactors is optimal. Designing a blanket that uses, e.g. 20 tonnes per GWe rather than ~100 tonnes, would make it feasible to use beryllium for five times as many fusion reactors (roughly the quantity of beryllium estimated to be in the U.S. Spor Mountain mine). Moreover, if a blanket using minimal quantities of beryllium and with no lithium-6 enrichment can be developed, this may present an optimal solution with respect to both beryllium and lithium-6.
7.5.3. **On the use of lead in tritium breeding blankets**

7.5.3.1. **Results**

![Figure 7-18](image1.png) **Lead required for small fusion reactors against global lead production capacity** (large fusion reactor not provided due to no meaningful disparity in results).

![Figure 7-19](image2.png) **Lithium-6 required for lead-based blankets for small fusion reactors with installed electricity generation shown for comparison** (large fusion reactor not provided due to no meaningful disparity in results).

7.5.3.2. **Lead availability and supply chain**

The resource base for lead (2 billion tonnes) does not appear to present a problem for the commercial rollout of fusion. To support the fusion industry at its maturity (1000 GWe installed per 3 years), around 1.4 M tonnes per year is required; a little over a quarter of
current global lead production at 4.4 M tonnes per year. As such, this research concurs with the previous assessment by Bradshaw et al. that lead resource is plentiful, but can further conclude that the supply chain is also ample (Bradshaw, Hamacher & Fischer, 2011). However, there are several problems that relate to its use that present different barriers to the use of beryllium.

7.5.3.3. Commercial issues with lead-based tritium breeding blankets

Firstly, the quantity of lithium-6 required for lead-based blankets is six times higher than for equivalent beryllium-based TBBs. For 20% electricity generating capacity, a total of 65,000 tonnes of lithium-6 will be required (requiring 1.7 MT natural lithium), compared with just 11,000 tonnes for beryllium-based blankets. Similarly, to support a fusion industry beyond 10% of installed capacity, the required rate of lithium-6 supply is 10,000 tonnes per year versus 1,500 tonnes per year for beryllium. As such, the supply of lithium-6 may present an additional cost to lead-based blankets not incurred for beryllium-based blankets. The cost of the lead is currently US$ 2,360 per tonne (2019$), which equates to lead resource for smaller and larger reactors costing ~US$ 2M and ~US$ 10M respectively; which, in both cases, is an insignificant cost. However, the higher percentage of enriched lithium-6 that is required may drive up cost significantly versus the cost of lithium-6 for beryllium. At the cost of US$ 4000 per kg (US$ 4M per tonne), the initial cost of lithium-6 for a lead-based blanket for a smaller and large reactor is ~US$ 17M and ~US$ 100M respectively.

A secondary cost is that of fabricating the lithium-lead eutectic. As early as the 1970s, fusion scientists suggested that “a large amount of liquid lithium metal [required for new fusion plants] represents a sudden, large increased demand equal to one-quarter of current annual consumption” (Walton & Spooner, 1976). However, the cost of producing lithium-lead, ignoring lithium-6 enrichment costs, is likely to be insignificant (Personal communication with Satoshi Konishi, Kyoto University).

Finally, a significant limitation that may affect the commercial viability of lead-based blankets is the production of polonium-210 (\(^{210}\text{Po}\)) and mercury-203 (\(^{203}\text{Hg}\)) (see 7.2.5). It would necessitate expensive purification systems, but also means that lead-based blankets would yield long-lived nuclear waste as the production of these isotopes is unavoidable and instead represents a problem to be managed. There are other similar costs relating to the performance of lead-based blankets, in particular, that large volumes of lead may be a driver on minimum device size; the power required for pumping; and development of materials to negate magnetohydrodynamic effects. These all have the capability to drive cost upwards but are secondary issues not central to the focus of this assessment.
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<th>Inventory (I\textsubscript{CRYO}) factor</th>
<th>Initial cryo* inventory (I\textsubscript{CRYO})</th>
<th>Initial HT** inventory (I\textsubscript{HT})</th>
<th>Annual cryo* losses (L\textsubscript{CRYO})</th>
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<td>MMscf (lifetime)</td>
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<table>
<thead>
<tr>
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<th>Annual helium refill (losses)</th>
<th>Total helium requirement</th>
<th>Total helium per unit power</th>
<th>Units</th>
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<td>lifetime MMscf per MWe</td>
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<th>Total helium per unit power</th>
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<td>lifetime MMscf</td>
</tr>
<tr>
<td>Total helium per unit power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>lifetime MMscf per MWe</td>
</tr>
</tbody>
</table>

*cryo indicates helium inventory for all cryogenic cooling, e.g. for magnet cooling, cryopumping and pellet injection. **HT indicates helium gas inventory for all heat transfer systems, i.e. for the TBB and divertor only.

Table 7-10 Helium requirements of small tokamaks using HTS magnets and large tokamaks using LTS tokamaks. HTS magnets are assumed to reduce the required helium inventory by half (Clarke & Cai, 2012). The bottom two rows represent the helium required to cool all systems, i.e. where all systems are cooled by helium, and a scenario in which the HT systems are cooled by, e.g. iLHe. Grey column shows helium inventory for a small tokamak using HTS magnets cooled by helium to understand scaling effects.
Figure 7-20  Graph showing helium demand for small fusion reactors using HTS magnets, with helium supply estimates from (Cai et al., 2010) and shows electricity generating capacity for comparison.

Figure 7-21  Graph showing helium demand for large fusion reactors using LTS magnets, with helium supply estimates from (Cai et al., 2010) and shows electricity generating capacity for comparison.
7.5.4. On the use of helium for fusion reactors

7.5.4.1. Results

As shown in Figure 7-21, in the case of large fusion reactors with LTS magnets, the results of the model suggest that global helium resource is sufficient to support a commercial fusion programme up to approximately 1700 GWe of installed electricity generating capacity. Interestingly, as shown in Figure 7-20, in the case of small fusion reactors with HTS magnets, the results of the model suggest that global helium resource is sufficient to support a similar capacity to large tokamaks using LTS. As such, the use of HTS magnets appears to negate the scaling effects that benefit larger sized reactors. Naturally, however, the results in this study naturally mirror the previous assessments upon which they were based – see the studies by (Clarke & Cai, 2012; Cai et al., 2010).

7.5.4.2. Cost of helium

The helium price is currently around US$ 210,000/MMscf (Grade A helium in 2019$, (U.S. Geological Survey, 2020)) but could rise to as high as US$ 500,000/MMscf by ~2070 (Cai et al., 2010; Clarke & Cai, 2012). At the current cost of helium, assuming all systems will be cooled by helium, the total (lifetime) cost of helium is US$ 4.8M for a small tokamak using HTS magnets and US$ 22.1M for a large tokamak using LTS magnets. The cost of helium for smaller tokamaks is lower, but the quantity of helium required is comparable per MWe, i.e. HTS magnets negate scaling effects with a larger reactor. Accordingly, large tokamaks using HTS would likely present an optimal solution as regards cost (not modelled) due to the combination of a reduced helium inventory and scaling effects. As regards the commercial viability of fusion, however, even if cost were to increase fivefold (~US$ 1M per MMscf helium), helium as a resource for fusion is not as significant as the cost of beryllium or lithium-6. However, designing systems that are not essential to be cooled by helium, i.e. those for cryogenic applications, to be cooled by other coolants provides an effective way of reducing cost.

7.5.4.3. Indirect hydrogen cooling for tritium breeding blankets

Helium is not dissimilar to beryllium in that it is likely sufficient to support the first generation of fusion reactors, but in the longer-term, as it becomes in short supply and becomes more expensive, it might not be sustainable. To facilitate the future shift away from helium cooling for fusion, the possibility of indirect hydrogen cooling blanket systems is considered.

The consideration of iLH$_2$ as a means to provide cooling for TBBs has not been seriously considered in the fusion industry, see (Clarke & Glowacki, 2010). Whilst it is clear that an
iLH$_2$ system for blanket cooling may save helium resource, it also may provide a much more cost-effective way of cooling. The power required to cool a material 4 K requires approximately five times more power than cooling to 20 K, per the diagram showing Carnot efficiency of refrigeration in Figure 7-22.

![Ideal (Carnot) Refrigerator Performance](image)

**Figure 7-22** Carnot refrigerator performance at different temperatures, reproduced with permission from (Ganni, 2009).

Therefore, if the inventory of helium can be reduced, and efficiency improvements can be made, then TBBs cooled by iLH$_2$ should be considered. Whilst near-term TBB designs can be based on helium, next-step reactor designs should consider iLH$_2$.

### 7.5.4.4. Separating helium from air: an alternative perspective

The majority of helium is produced by extracting it from natural gas. Whilst helium may be available; it is inherently tied to fossil fuels, see (Cai et al., 2010). Helium, therefore, adds to the carbon footprint of fusion. It is currently possible to separate helium from air by means other than from natural gas, but it is currently not economical. Both Bradshaw and Hamacher and Clarke and Cai suggest – with differing levels of optimism – that extracting helium from air via an ASU (Air Separation Unit) as an integral part of a fusion reactor could avoid the helium resource problem altogether (Clarke & Clare, 2012; Bradshaw & Hamacher, 2013). Clarke and Clare suggest that 0.5% to 1% of the energy from a fusion reactor would need to be diverted to produce helium whilst presenting the opportunity to produce other products too, such as oxygen. Future fusion power plant designs with ASUs to obtain helium from air can improve the sustainability of the technology and can also – via
the sale of air separation products – present a route to commercialisation. This aligns with the earlier suggestion for medical isotopes as a commercial pathway for fusion (see 6.3.6.4 and (Kulcinski & Santarius, 1998)). Further, the notion that the production of helium-3 from tritium should be considered for all future commercial fusion reactors as a by-product\(^{229}\). Together, an ASU and other isotope production from fusion should be further explored as a near-term commercial route for fusion. As detailed in the earlier chapter of this thesis, such commercial opportunities should be considered as a driver near-term technology development.

7.5.5. On reactor size and resource use

Total resource required for both large and small fusion reactors is the same per GWe. Thus, the same installed capacity of large or small reactors will require the same amount of resource (assuming no scaling effects). However, it is in the rate at which fusion reactors will be deployed that there are important differences between large and small reactors. A smaller fusion reactor requires less resource in the early stages of rollout. Several reactors can be built and tested (both from a technological perspective and in the market) for every one larger reactor. Even if – hypothetically – a 200 MWe reactor was subject to scaling effects such that it requires three times the quantity of resource compared with a 1 GWe reactor, the cost of resources would still only be 60% of the cost of that 1 GWe reactor. Irrespective of whether smaller reactors are more cost-effective per unit power in the long-term, i.e. due to scaling effects, but reducing the size of the reactor in the near-term would proportionally reduce the capital cost (also see (Woodruff & Miller, 2015)). This would mean that the first fusion reactors could be tested at a smaller scale before scaling-up.

Smaller fusion reactors thus present less of an investment risk in the earliest stages of the commercial deployment. Without the guarantee that fusion will be viable in the market, it is difficult to justify the large investment and guarantees required to ramp up the materials supply chains, at least not without government backing (which still represents a risk, it is only that the risk is shouldered by governments rather than by markets). Starting small allows time to assess whether the technology will be successful in the market. Accordingly, fusion developers should choose resources that are plentiful, and which have robust supply chains. Smaller fusion reactors thus represent a more cost-effective and lower risk route to the first commercial fusion power plant. This is particularly true when considering the beryllium supply, which is subsequently discussed.

\(^{229}\) See 6.3.6.4.
7.5.5.1. Smaller is better for the beryllium industry

In the near-term, there is a key difference between the two approaches to use large or small reactors regarding the rate at which beryllium is supplied. The current capability of the beryllium industry (~400 tonnes per year) is sufficient to meet the resource requirements of one or two large fusion reactors per doubling time. Notwithstanding a significant change in the beryllium market, the existing supply chain is ample to supply beryllium for a fusion development programme based on small reactors, and is sufficient to build between five and 10 smaller reactors in the same time it takes to build one or two large reactors. The cost per reactor is also – obviously – reduced, with the large and small reactors costing US$ 34M and US$ 170M, respectively (2018$).

![Cumulative beryllium demand for the first 32 fusion reactors (small and large).](image)

Referring to Figure 7-23, the beryllium industry has a period of approximately 15 years ramp up its supply chain to meet upcoming fusion demand based on the deployment of the first 32 small reactors. The first 32 large reactors, by contrast, require the beryllium industry to scale up in just seven years. Whilst for both pathways, the capability to supply resource does indeed limit the rapid expansion of fusion (as is the case for many energy technologies), starting small allows more time to prepare for the scale-up. Deploying a larger number of reactors in that process of scaling up both reduces the risk in the market, and also increases the possibility for learning. The experience from the first 32 reactors can be used to inform the beryllium industry based on how the market responds to the fusion technology. In other words, it allows the economic competitiveness and social acceptability of fusion to be demonstrated more fully before the beryllium industry fully invests in ramping up supply chains (see discussion in 7.5.2.3). This is true not just of beryllium resource supply, but also for other aspects of the beryllium supply chain, e.g. pebble production, which will also require cost and time to ramp up (Personal
communication with Aniceto Goraieb, Karlsruhe Beryllium Handling Facility, Germany, and Christopher Dorn, Beryllium4Fusion).

7.5.6. Limitations of the model

Some limitations of the model have been detailed throughout 7.4. However, three specific limitations are discussed further.

7.5.6.1. Static forecasting

The model does not assess the dynamics of lithium, beryllium, or lead supply, e.g. the effects that fusion demand for these resources might have on cost or market response\(^{230}\). Static forecasting was pursued as this research represents the first comprehensive assessment of TBB resources compared with previous studies (noting that studies from the 1970s are comprehensive, but out of date). Hence, this study provides a basis for further enquiry into the specific challenges associated with each of the key resources outlined.

7.5.6.2. Recycling of blankets

If blankets were replaced at, e.g. 5 to 10-year intervals, then this places a requirement on a new resource to be supplied for fusion than the rollout model suggests. Whilst recycling, if employed, could contribute to resource supply, this will come with the added cost and a time delay. A fusion reactor that needs a full blanket change every 5 to 10 years will put substantial additional strain on the available resources, and simultaneously increase the cost (noting the cost of lithium-6 and beryllium, let alone blanket fabrication costs). Unless blankets can be designed with replacement and recycling in mind or use materials that are not scarce or expensive, blanket technology could become the key issue to fusion commercialisation.

7.5.6.3. Fusion for electricity generation

Fusion is assumed to only supply electricity, and fusion to address other primary energy challenges, e.g. for process heat applications such as desalination (see 5.4.1.2.2), are not considered. Whilst this is a limitation of the model, it also shows the scale of the challenge for fusion to supply clean energy. Global electricity generation is approximately 40% of primary energy demand and constitutes only 18% of global carbon emissions (International

\(^{230}\) Whilst this study does not use assess the impact of updated helium demand considerations on the dynamics of the helium market as in (Clarke & Cai, 2012; Cai et al., 2010), it adopts the assumptions from that study.
Energy Agency, 2017). If deep decarbonisation is the goal for fusion energy, then the technology must be developed to address more than just electricity generation. The required fusion rollout likely needs to be at a rate one order of magnitude higher than at current if it is to solve all the world’s energy problem. Such a feat would require a far greater quantity of resource. Importantly, and quite bluntly, it also shows the scale of the challenge and the capability, or lack thereof, of fusion to address the energy challenge on its own.

7.6. Conclusions: towards an optimal tritium breeding blanket

7.6.1. Characterisation of commercial drivers by critical resources

The analysis and discussion of critical TBB resources allow for conclusions to be made regarding a commercially optimal TBB. However, it is unlikely there is a single blanket design that will offer a route to a commercial D-T fusion reactor that avoids any of the challenges that have been uncovered and discussed in this chapter. Moreover, none of the existing blanket designs is likely to be suitable for a commercial reactor, as blanket R&D has – perhaps rightly, and perhaps due to a linear innovation model – focused on technical challenges rather than commercialisation. However, this research has explicitly considered those commercial considerations. These can be summarised with respect to each of the blanket resources that have been studied:

- Beryllium must be used in as small a quantity as possible due to resource scarcity and – to a lesser extent – cost.
- The production of lithium-6 is effectively zero. Production is likely to be costly, but more pertinently, there are potentially stringent regulatory requirements that will apply to the production of lithium-6 for fusion. Natural lithium, conversely, offers no substantial risk; is in ample supply, and is low cost.
- Lead produces radioactive waste, specifically polonium-210 and mercury-203. Lead requires a particularly high level of lithium-6 enrichment, and thus it is unlikely to be compatible with natural lithium as a blanket concept. Thus, all blankets based on lead will produce radioactive waste and will require lithium-6 infrastructure and the associated challenges (see above).
- Helium is plentiful in the near-term, but in the longer-term, iLH₂ cooling as well as ASUs should be considered for fusion helium.

7.6.2. Commercially optimal tritium breeding blankets

In the near-term, beryllium supply capability may be limited, and absolute resource limits on beryllium render it unviable as a long-term solution. On the other hand, beryllium-based breeder blankets require lower lithium-6 enrichment versus lead-based blankets.
Regardless, any enrichment of lithium-6 is deemed unfavourable and thus all current designs, including beryllium blankets that typically foresee 30% lithium-6 enrichment, are potentially not commercially viable. Currently, production of lithium-6 is zero, and there are potential barriers to commissioning a lithium-6 production facility and exporting lithium-6 for use in a fusion power plant without stringent regulation. As such, current designs for lead-based blankets, which are dependent on high enrichment of lithium-6, are not likely to be commercially viable.

Despite issues with lithium-6, lead and beryllium, it appears that helium is readily available as a coolant for at least the first 1000 GWe of commercial fusion reactors. Even though there are challenges in the long-term, solutions such as extraction of helium from air and a significant reduction in helium requirement via iLH$_2$ cooling have been identified. Similarly, that water provides a substitute coolant to helium, albeit that it limits performance, means that helium supply for fusion is categorically different to lithium, and beryllium and lead – all of which cannot be substituted. As such, what an optimal blanket might look like from the perspective of lithium-6, beryllium and lead based on the aforementioned challenges can be outlined. Two blanket solutions that could be considered optimal are suggested:

1. The first is a beryllium-based TBB that uses natural lithium. With a reduction from 109 tonnes per GWth to, for instance, 50 tonnes per GWth, beryllium-based blankets may be viable for the first generation of fusion reactors. From the data in this model but with a reduction to 50 tonnes per GWth, then 100 GWe of installed capacity would require roughly 12,000 tonnes of beryllium (not including burn-up). However, considering the issues with the scaling-up of the supply chain, the optimal route would be via smaller fusion reactors requiring less resource during the early stages, to allow the beryllium industry to adapt. Finally, in order to keep the cost down, and to avoid the issue of lithium-6, it is concluded that a beryllium-based blanket should be designed to use natural lithium (if technically feasible). Even so, this route may only present a solution for the near-term up to, perhaps, 1000 GWe installed capacity. In the longer-term, alternatives are needed.

2. The second is a lead-lithium blanket using natural lithium and very small quantities of beryllium to boost neutron yield (in the order of tonnes). This blanket, if technologically feasible, would present a viable option as both lead and natural lithium are abundant and cheap. The small quantities of beryllium, which provide additional neutron multiplication, could permit the use of natural lithium in a lead-based blanket (which, based on current designs, typically require enrichment to 90%). One drawback of this approach is the production of radioactive isotopes in lead. However, it is suggested that if there is public, regulatory, and industrial
acceptance of the waste issue – which is not restricted to fusion blankets – then such a blanket could provide a long-term commercially viable solution.

7.6.3. Innovation in tritium breeding blanket design

As detailed in the earlier chapters of this thesis, the commercial drivers from this assessment, together with the technical constraints, are essential for successful innovation. Two commercially viable blankets have been outlined based on the findings of this study. The suggested commercially optimal blankets are not necessarily technically feasible or optimal. As such, both the commercial and technological perspective should be considered in parallel – possibly via an effectively designed roadmap specifically focused on blankets – to understand where the two sets of drivers overlap. As a result, a new “blanket innovation space”, in which a novel solution can be developed, can be identified. All fusion efforts should be focused on developing blanket technology, and indeed all other technology, consider both such drivers.

7.7. Chapter Summary

This chapter has presented a comprehensive assessment of the critical resources required for commercially viable TBBs. Gaps in the literature have been addressed through the development of a commercial rollout model to forecast the demand for critical resources for fusion. The results of the model, as well as extended analysis and discussion with reference to literature not previously contextualised in the fusion research space, has provided findings into the availability, supply and use of lithium-6, beryllium, lead and helium resource. In particular, key problems were identified with lithium-6 and beryllium. The production of lithium-6 for fusion is likely to be subject to stringent regulation, and, currently, no supply exists. Challenges with the availability and supply of beryllium suggest that a commercial fusion programme could not depend on beryllium past the first stages of commercial rollout. However, in such a scenario whereby beryllium-based breeder blankets are pursued, smaller fusion reactors are favourable in the early stages of a commercial programme. Finally, the challenges with all resources have been collated, and two potentially commercially optimal TBB designs outlined. It is suggested that the commercial drivers identified to be considered in parallel with technology development programmes. This study thus opens up a new blanket innovation space.

Refer to Hoedl’s “social license” for nuclear technologies (Hoedl, 2019).
This chapter, along with the research presented in Chapter 6, has addressed research question 3. In Chapter 8, the subsequent and final chapter of this thesis, the findings from both chapters are collated with the findings of previous chapters to conclude this thesis.
Chapter 8. Summary, Conclusions and Recommendations

This chapter outlines and discusses the key contributions of this thesis and explicitly addresses the research questions. 8.1 summarises and collates key outputs of the research. 8.2 outlines research findings against the initial research questions. 8.3 details the specific contributions of this thesis to the existing research theory as well as practice. 8.4 details the limitations of this research, which facilitates recommendations for future work in 8.5. Finally, 8.6 provides reflections on this research from the researcher.
8.1. Research Summary

This thesis has characterised an innovation paradigm shift in fusion towards start-ups in recent years. A roadmapping process has been developed, via a fusion start-up case study with Tokamak Energy Ltd, to support innovation management. Finally, the availability, supply and use of critical resources for fusion was identified as a key challenge to commercialisation and thus explored in-depth.

The public fusion programme was found to operate on a linear model of innovation – typical of publicly-funded government-led scientific endeavours – in which reactors that are not well suited for commercialisation are being pursued. By contrast, fusion start-ups are focused explicitly on commercialisation and have a need to satisfy investors, operate on a fundamentally different model of innovation: agile innovation, whereby technology is developed in an iterative manner. The approach is similar to companies in the space exploration sector, such as SpaceX. Along with parallels to the space sector, the well-established principles of agile, lean and open innovation are applied to the fusion start-up problem. The differences between the fusion start-up and the public programme approach to innovation are compared, with the most notable being that start-ups have a higher tolerance for risk, focus on the speed of developing via iterations of build-test-learn, and have an explicit focus on commercialisation (see Table 2-3). Finally, the pathway to commercialisation of fusion via a series of demonstrators is considered in the context of a model showing the innovation process. The public fusion programme follows a linear trajectory in which this series of demonstrators are deployed with lengthy timescales between iterations. Fusion start-ups – whilst accepting greater risk – are, by contrast, pursuing reactor designs that are simpler, smaller, and low cost, so they are able to iterate faster. Simultaneously, fusion start-ups also consider the requirements from the market diffusion stage of innovation – the commercial drivers – that must also be considered in early-stage product design. These two factors, taken together, suggest that fusion start-ups are operating on an agile model of innovation with an inherent commercial focus. It is contended that this represents a more effective approach to innovation.

Fusion start-ups must navigate and manage the innovation process if they are to achieve commercial success. “Futures” methods to support innovation management, i.e. to guide the process were considered for their suitability for the fusion start-up problem. Technology Roadmapping was found to be a suitable method in particular due to its function to map the stages of innovation and to thus account for both technical and commercial drivers. Accordingly, a novel roadmapping process – designed to encapsulate the fusion start-up approach to innovation previously outlined – was developed via a fusion start-up case study with Tokamak Energy Ltd. The process to create, develop and continuously iterate a roadmap has been comprehensively detailed, with a specific focus on the tools and
techniques, including workshops, that were developed and adapted specifically to the fusion start-up context. Elements of agile, lean and open innovation as previously detailed were also built into the process. For example, the process was designed to be updated in line with agile iterations to help guide and inform planning for next-step developments whilst providing a view of the longer-term commercial pathway. Furthermore, to support open innovation, the roadmap was designed to support the identification of potential collaborators and external opportunities. The process and outputs from the application at Tokamak Energy were objectively analysed with reference to the literature, specifically to understand how they supported planning, innovation, and also communication. In particular, the research provided insights into how roadmaps can facilitate internal and external (i.e. public) communication and how roadmaps can be used to communicate programmatic risk. Finally, whilst the roadmap defined “strategic milestones” to represent commercial drivers, it was later determined that market drivers to link technology development to commercial needs was necessary and should be incorporated. The research was presented such that the process and outputs could be readily applied to support fusion start-ups other than Tokamak Energy as well as similarly high-tech hardware-focused start-ups.

The research into innovation and roadmapping for the fusion start-up problem necessitated an interdisciplinary focus. However, none of the issues to the commercialisation of fusion had been analysed in-depth. In the development of the roadmap for Tokamak Energy, several key challenges that may impact the pathway to commercialisation were identified. Although many challenges were specific to Tokamak Energy’s mission, the availability, supply and use of critical natural resources for fusion is a key challenge affecting all fusion approaches – public and private, tokamak or non-tokamak. Principally, due to the emphasis on technology development, issues relating to commercialisation have, in comparison, received limited attention in fusion research. Several critical natural resources, all of which can be considered critical for D-T fusion, either as direct fuels, i.e. deuterium and tritium, or as resources required to breed tritium in blankets, were identified.

The availability of tritium – which is limited on Earth but required for fusion R&D, but will later be bred via tritium breeding blankets, was assessed. Analysis of the results of a forecast model provided insights into the supply and use of tritium, principally that Romania presents a potentially crucial source for the supply of tritium for fusion, and that multiple future fusion reactors may not be possible on existing tritium supply. Deuterium supply and use were analysed to understand potential barriers to commercialisation, representing the first substantial analysis of deuterium for fusion. Resources necessary to breed tritium were also explored. Lithium (specifically lithium-6), beryllium and lead (as neutron multipliers), and helium were assessed using a model which forecasted the rollout of commercial fusion. Several challenges were identified for each of the resources as having the capability to limit the commercialisation of fusion. In particular, beryllium and lithium-6 may present a
constraint from the perspective of availability, whilst deuterium and lithium-6 may present challenges as regards their use, specifically relating to export control, lack of supply chain capability and routes to proliferation. Finally, the analysis informed what a viable tritium breeding blanket might look like from the commercial perspective, defining a new blanket innovation space.

In summary, this thesis is focused on the pathway to the commercialisation of fusion. Beginning with a broader view from the perspective innovation, the key aspects of fusion development are characterised to substantiate that fusion is undergoing an innovation paradigm shift (to a new model of development). Subsequently, a means to manage and navigate the process of innovation towards commercialisation using Technology Roadmapping was developed specifically for the fusion start-up problem. Finally, the availability, supply and use of natural resources were analysed to provide insights on a key issue on the pathway to commercialisation. Combined, the findings of this thesis can be used to understand and support the development of a pathway to faster fusion, particularly for fusion start-ups.

8.2. Research findings

Research findings are presented here with reference to specific research questions.

8.2.1. Research question 1

What are the differences in the approach to innovation by government-led publicly-funded fusion programmes and privately-funded fusion start-ups?

With reference to literature from outside of fusion research, this research has characterised the innovation approach for the public fusion programme and for fusion start-ups. The public fusion programme follows a linear innovation model in which commercial aspects are not considered until later in the development programme. In contrast, although focused on demonstrating their specific scientific approach, fusion start-ups are also driven by the goal of commercialisation. Fusion start-ups accept a higher level of risk in order to facilitate progress, and there is an inherent focus on demonstrating that progress towards a commercial goal. Whilst both the public fusion programme and fusion start-ups foresee the pathway to fusion via a series of demonstrators (see 2.6.3), the approach to development is different. By – generally – keeping devices smaller, simpler and cheaper, fusion start-ups can progress via rapid “build-measure-learn” cycles, developing technology iteratively and dynamically towards a commercial goal. By understanding innovation as dynamic, and characterising the fusion start-up approach in the context of agile, lean and open innovation, the key differences with the public fusion programme can be summarised:
- Fusion start-ups are following a dynamic innovation approach which considers both technical and commercial drivers.

- To facilitate rapid progress, start-ups typically pursue the development of low-cost, small and simple devices relative to the public fusion programme.

- Accordingly, such devices are developed via iterative development, encompassing an approach aligned with agile and lean innovation to “build-measure-learn” and “plan-do-check-act” towards a commercial product, via a series of demonstrators (MVPs, see 2.5.7.1) on accelerated timescales.

- Such timescales are plausible as start-ups proceed in spite of unknowns and accept risk in favour of demonstrating progress.

The different technical approaches pursued by fusion start-ups represent challenges which may not prove viable from the technical perspective. Because this matter is not addressed in this thesis, it cannot be concluded whether fusion start-ups are pursuing a technically optimal path. However, this thesis does contend that an innovation paradigm shift towards fusion start-ups is underway and that fusion start-ups represent a more effective approach to innovation than the public programme.

8.2.2. Research question 2

A. Can an innovation management method be adapted to fusion start-ups – which operate on an agile innovation model – to support the commercialisation process?

B. Consequently, how can the development and application of Technology Roadmapping support fusion start-ups?

Methods to support strategy, planning and innovation – all of which have been previously applied to a variety of industrial contexts – were explored to understand suitability to fusion start-ups. Although methods such as Delphi and Scenario Planning were deemed useful Futures methods, Technology Roadmapping was judged to be the most suitable method for the fusion problem. Roadmapping is detailed as a flexible and adaptable method that can accommodate various management tools and techniques. In particular, roadmapping allows the technical and commercial drivers to be considered in parallel and, due to its highly visual format, can be used to map the pathway to commercialisation. The roadmapping method was applied to Tokamak Energy as a fusion start-up case study with the aim of supporting planning, innovation and communication. A novel process to create, develop and continuously iterate a roadmap for Tokamak Energy was produced. Various tools, techniques and features were built into the process, including linkage grids to connect technology development to commercial drivers. The process supported planning, e.g. by identifying and characterising TGIs and the relevant “method of resolution” to resolve it.
The process also supported innovation, e.g. by the way in which the process can be aligned with agile innovation cycles. Conversely, however, the need for an explicit layer of the roadmap to consider commercial (“market”) drivers was identified as a key limitation (see 5.4.1.2). The process was focused on facilitating internal and external communication, which yielded views of the roadmap to be useful for public communication and to assess programmatic risk.

In summary, a novel roadmapping process has been developed through deployment with a fusion start-up. The process, its outputs and the analysis presented in this research demonstrate that an innovation management method – Technology Roadmapping – can be used to support fusion start-ups in the management of the commercialisation process. In particular, it can be used to facilitate planning, innovation and communication. The process as developed can be adopted by other fusion start-ups or similarly high-tech hardware-focused start-ups pursuing agile innovation.

8.2.3. Research question 3

*What are the issues surrounding the availability, supply and use of critical fuels for D-T fusion, and how do they affect the route to commercialisation?*

The results from this research suggest that – despite delays – tritium is likely to be available for the operation of ITER. Further, until ITER starts in 2035, there is a window of opportunity in which tritium is available for fusion start-ups, but potential challenges with its supply and use, particularly relating to regulation and international trade. Unlike tritium, deuterium is abundant and future supply for fusion ample, subject to investment in the supply chain. However, there are issues relating to the supply and use of deuterium, particularly regarding export control and potential pathways to proliferation. This thesis has analysed and discussed such issues as potential barriers to commercialisation.

Whilst externally sourced CANDU tritium can be used for R&D, tritium breeding blankets – which have been the focus of development for decades – are required for commercial fusion reactors. Tritium breeding blanket development has, like many areas of fusion research, neglected the commercial perspective. This research has explored the commercial challenges associated with the availability, supply and use of critical resources for tritium breeding blankets (lithium, beryllium, lead and helium). A model forecasting the commercial rollout of fusion was produced, showing the expected supply and demand for each of the resources and key commercial challenges were analysed and discussed. While natural lithium resource is abundant, and supply expected to be ample, it was found that lithium enriched in lithium-6 – essential for tritium breeding blankets – is not produced in any significant quantity and thus supply is effectively zero. Furthermore, the use of lithium-6 is
subject to export control and has potential pathways to proliferation. Similarly, beryllium was found to be scarce on Earth, and the industry’s supply chain is insufficient to support a commercial fusion programme in the long-term, or perhaps even the near-term. Conversely, lead – an alternative neutron multiplier to beryllium – is abundant and the supply chain ample. However, lead-based tritium breeding blankets can produce long-lived radioactive isotopes and also necessitates a higher enrichment of lithium-6 and, hence, the aforementioned problems with lithium-6 enrichment apply. Finally, using data from previous assessments, it is found that the helium resource remains abundant in the near-term but – as previous studies concluded – may become scarce beyond 2050 (see Clarke & Cai, 2012). This research provides new insights into the supply of helium for fusion. In particular, if the choice is made to pursue hydrogen cooling (iLH2) for the heat transfer systems and for advanced HTS magnets (currently under development for tokamak-type fusion reactors), then the quantity of helium required for a commercial fusion reactor could be significantly reduced.

Two commercially optimal blankets are outlined which – broadly – conclude that blankets foregoing lithium-6 enrichment, and which use only limited quantities of beryllium are favourable. Lead-based blankets using enriched lithium-6 blankets are also plausible if the waste issue is treated as a problem to be managed, and the potential regulatory and proliferation issues are accordingly acknowledged and resolved. However, such a route may affect the public acceptance or the ability for the global deployment of fusion. Finally, whilst in the near-term tritium breeding blankets can be designed to use helium as an optimal coolant (versus water), in the long-term the extraction of helium from air twinned with an iLH2 system may allow future fusion power plants to be self-sufficient on helium.

In summary, the availability, supply and use of critical resources are considered as potential barriers to the commercialisation of fusion. By characterising the commercial drivers, this research has defined a new “blanket innovation space” which can be used to complement existing technical knowledge to facilitate the development of new commercially viable blanket designs.

### 8.3. Contributions from this thesis

This section details the key contributions of this thesis to theory and the literature (8.3.1) and the to practice (8.3.2).

#### 8.3.1. Contributions to literature and theory

Firstly – and importantly – the research as presented in this thesis is wholly interdisciplinary. Research methods and concepts from the fields of innovation and management have been
applied to the fusion research field, which is heavily focused on science and technology. The combination of cross-cutting ideas and analysis presented in this thesis thus presents a novel contribution in itself. Other specific novel contributions from this research are detailed below:

- Innovation theory has been used to characterise the innovation paradigm shift towards fusion start-ups. The characterisation of the public fusion programme compared with start-ups from the perspective of innovation models; the approach to development; the approach to risk; the focus on demonstration; and the parallels with historical innovation and current space exploration start-ups represents a novel view of fusion innovation. Also see (Pearson et al., 2020).

- The application of agile and lean innovation, specifically, the iterative approach to development; the importance of reducing waste (time or resource); and the focus on developing towards an MVP to facilitate the understanding of the innovation approach of fusion start-ups. Also see (Pearson et al., 2020).

- The roadmapping process developed in this research represents an application of Technology Roadmapping applied to agile innovation for high-tech, long-timescale hardware problems. The process developed encompasses aspects of the fusion innovation approach (see the previous point). Accordingly, this application informs a gap in the roadmapping literature. Also see (Pearson et al., 2020).

- The application of roadmapping in a fusion start-up case study has provided contributions to specific areas within roadmapping research:
  
  o Roadmaps for public communication. The research has explored how roadmaps can be used to generate investment and to convey messages to external audiences. Further, how roadmaps can support the reduction of information asymmetry was also analysed and discussed, contributing new insights ideas to existing research, specifically (Kerr, Phaal & Probert, 2012; Kamtsiou et al., 2006) (see 5.5.2).

  o Roadmapping for understanding and communicating programmatic risk, building on and developing existing research, specifically (Ilevbare, Probert & Phaal, 2014; Kappel, 2001) (see 5.5.3).

  o The understanding of how roadmapping differs to traditional project planning (e.g. Gantt charts), which is not clearly discussed in the literature, is a contribution arising from the practical implementation of roadmapping (see 5.6.1.3).

The contributions from Chapters 6 and 7, the commercial challenges associated with critical natural resources for fusion, are summarised:
The assessment of tritium supply provided new analysis, particularly as regards the international supply of tritium and tritium available for start-ups. The research built upon previous research ((Ni et al., 2013)) and complemented parallel work ((Kovari et al., 2018)).

Deuterium as a fusion fuel has not been extensively explored in the literature, and this research challenges the existing understanding of the availability, supply and use of deuterium. The analysis considered issues omitted in previous work, including by ((Von Hippel et al., 2012; Ward, 2007; Bradshaw, Hamacher & Fischer, 2011)). In particular, key challenges relating to export control and potential pathways to proliferation were analysed.

Critical natural resources required for tritium breeding blankets were considered in the context of a commercial fusion programme which provided a greater depth of analysis and discussion of the issues than previous studies (see (Bradshaw, Hamacher & Fischer, 2011; Rhinehammer & Wittenberg, 1978)). The research provided new perspectives on commercial issues associated with tritium breeding blanket development and challenges some existing ideas, including issues with the availability and cost of beryllium; issues with the use of lead; and issues relating to the production, international trade and potential pathways to the proliferation of lithium-6 (as well as deuterium) that may limit the global deployment of fusion.

The comparison of smaller fusion reactors versus larger fusion reactors suggests that it is more efficient to pursue smaller reactors (assumed to be operating at lower power; 200 MWe versus 1 GWe) from the perspective of natural resources. Keeping the quantities of natural resources low during the development phase means that existing supply chains are ample, particularly in the context of beryllium and lithium-6, and the costs are lower.

Finally, and importantly, this thesis contributes to a growing body of research focused on the fusion start-up approach\textsuperscript{232}, providing key contributions from the innovation, management and resource perspectives.

8.3.2. Contributions to practice

Several aspects of this thesis provide contributions to practice, which are outlined below:

\textsuperscript{232} See (Costley, Hugill & Buxton, 2015; Costley, 2019; Wurden et al., 2016) for the physics perspective; (Whyte et al., 2016; Sorbom et al., 2015) for the engineering perspective; (Rothrock, 2016; Ingersoll, 2017), (Kulcinski & Santarius, 1998; Nuttall, Glowacki & Clarke, 2005) for the commercial perspective; and (Lopes-Cardozo, 2019; Lopes Cardozo, Lange & Kramer, 2016; Locatelli, 2017) for the economics perspective.
The characterisation of the innovation approach for fusion start-ups (see specifically Table 2-3) provides a prescription for fusion start-ups to increase the agility, leaness and openness of their innovation approach.

The developed roadmapping process developed is based on the innovation principles outlined in Chapter 2, and thus provides a practical application of theoretical and conceptual innovation theories. In particular, the way in which the process adopts aspects of the innovation organisation model – e.g. the importance of collaborators and partners to support internal development – thus provides a practical manifestation of what previously existed only as a conceptual model (as developed by (Bonvillian & Weiss, 2015)).

The roadmapping process provided Tokamak Energy with several practical benefits, mostly relating to innovation management. Whilst these were specific to the company as the subject of the case study, the distillation of these benefits has implications for other fusion start-up companies to which the framework is generalisable. These are summarised here:

- The roadmapping process provided the company with a tool for the practical implementation of agile, lean, and open innovation theory. Specifically, the roadmap supported high-level planning for the company’s innovation cycles (agile innovation); separated development challenges into swim-lanes to understand how technology development could be tackled in parallel (lean innovation); and, through the methods of resolution, provided a means to identify potential external collaborators to resolve problem areas, analogous to a “make or buy” decision tool (open innovation).

- The scope of the roadmap showed the company’s trajectory to a first commercial prototype. This provided a more holistic systems view of the other actors and drivers, including commercial drivers, that must be considered to achieve the company’s goals (rather than a sole focus on technology development).

- Relatedly, the roadmap thus provided a view of the linkages between the technology and, for instance, company capabilities and commercial aspects associated with the development of that technology. As such, the roadmap provided a tool to identify and account for non-technical drivers in the development of technology.

- Interdependencies across disparate technology streams were identified using the TGI linkage grid. This informed detailed technology R&D planning at Tokamak Energy.

- Related to both the separation of parallel technology development streams and the methods of resolution, the roadmap – providing an integrated view of all the components in the engineering system – informed recruitment.
The derivations of the roadmap, specifically the public communications roadmap, has provided Tokamak Energy with a tool to communicate their technology development strategy and route to market. It has been used as a visual tool for public relations and in investor pitches. Further derivations of the roadmap, to show IP opportunities or investment requirements, could be used for similar strategic purposes.

- The article published by the PhD researcher in the Journal of Technology Forecasting and Social Change distils the key findings from the roadmapping action research and presents them in the form of a roadmapping framework which can be applied to other fusion start-ups, see (Pearson et al., 2020). The developed roadmapping process, if reproduced by other fusion start-ups (or other high-tech start-ups with a similar focus to fusion start-ups), can support the creation, development, and implementation of roadmapping, to yield similar practical benefits as Tokamak Energy.

- Specific tools or processes developed in this research, as well as the lessons learned, such as the process to design roadmaps to assess risk and to facilitate communication, can be recreated or modified to support other fusion start-ups or companies in other similar industrial contexts.

- Global suppliers of tritium, the quantities of tritium available and the potential supply constraints that must be overcome have been identified. Specifically, the potential for Romania to produce tritium for global fusion programmes and for fusion start-ups to use tritium before the operation of ITER has been indicated.

- The perspectives provided on tritium breeding blankets can be used to inform the development of fusion policy, e.g. to inform the establishment of a regulatory framework for the international supply of critical blanket resources.

- Research into blanket resources has opened a new “innovation space” for commercially viable tritium breeding blankets.

### 8.4. Research Limitations

Key limitations to the overall research are detailed.

#### 8.4.1. Fusion innovation

Whilst the interdisciplinary nature of the research presented in this thesis is itself part of the value of its contribution, it is also a limitation. The later chapters of this thesis have provided

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233 Refer to 6.3.6.4 regarding the decision to commission a helium-3 extraction facility to the Romanian CTRF, which is a practical contribution from this research (see (Pearson et al., 2017)).
an in-depth analysis of a specific topic – natural resources. However, the first half of this thesis – and specifically chapter 2, which underpins the research developed in chapters 3 to 5 – is inherently interdisciplinary, which naturally provides breadth. Albeit that breadth is necessary and indeed useful to link cross-cutting research areas, such breadth in exploring multiple research areas can lead to a lack of depth. Furthermore, breadth rather than depth can lead to misconceptions about each area in an attempt to produce a link. For example, chapter 2 attempts to collate ideas in what is a complex and expansive research area, often heavily based on conceptual models and ideas. The innovation models, as characterised in this thesis, as well as the understanding of agile, lean and open innovation, may have been misinterpreted. Whilst the research presented has been conducted in a comprehensive and objective manner, with ideas interpreted and substantiated with reference to the literature, the research would benefit from further analysis.

The innovation framework presented for fusion start-ups represented a theoretical construct. Although it was applied and thus manifested to underpin the roadmap later developed, to some extent proving its practical and well as theoretical viability, the ideas presented need to be considered in the context of further real-world environments and contexts, including with insights from other similarly high-tech start-ups outside of the fusion space.

8.4.2. The application of roadmapping to fusion start-ups

Although potential sources of bias have been acknowledged (see 5.1), the roadmapping process developed in this research was inherently biased towards the needs of Tokamak Energy. Whilst the process is presented objectively, with reference to the Tokamak Energy application for context or for illustration, to understand its effectiveness, the process should be adopted and accordingly adapted to other similar start-ups.

As regards the roadmapping process itself, whilst based on existing frameworks and processes, there were several aspects that were not considered in-depth:

- The research lacked focus on the embedding phase of the roadmapping process, i.e. how the process is taken up by the organisation after it has been developed. The factors that may have led to this are discussed in 5.6.1.1 with reference to the existing literature, specifically (Gerdsri, 2007). If this research were repeated, strategies to better implement the roadmapping process in the organisation should be of greater focus.

- With respect to the process itself, a significant limitation was in the use of TRLs, which – as discussed at 5.3.5 – were difficult to apply to fusion development. Whilst the attempted application of TRLs to support roadmapping in this research provides some useful lessons. Naturally, the failure to fully implement them represents a
limitation. The complexity of TRLs should be explored in greater depth and a roadmapping approach that encompasses levels of TRLs, SRLs and IRLs, should be adopted.

- Finally, as discussed in-depth in 5.4.1.2, the lack of an explicit markets layer in the Tokamak Energy roadmap represents a significant limitation. Limiting the understanding of external drivers and how they may affect internal development could result in the development of programmes that are inward-looking, i.e. not angled towards commercialisation.

8.4.3. Critical natural resources for fusion

Specific limitations with the two resources forecast models are detailed throughout Chapter 6 and 7. More broadly, however, the overall limitations of this research into the availability, supply and use of resources are twofold:

- Although the research presented in this thesis provides greater depth than previous studies, it still represents a high-level analysis. This was necessary as this thesis broaches issues that have not yet been addressed in a significant level of depth in the literature. However, further analysis is needed to validate the assertions and challenges that have been characterised. In order for the analysis and discussion points from the resources chapters to inform policy and regulatory decisions, for instance, further work is needed, perhaps including involvement from national and international regulatory organisations such as the International Atomic Energy Agency.

- Whilst there was a rationale to omit certain resources from consideration in Chapter 7, there are still problems with other resources that are not exposed or explored in depth in this thesis. In particular, the materials required for tritium breeding blankets to enable long operation lifetimes, e.g. materials for RAFM steels, should be considered in a similar way to the other resources considered in this research. Similarly, the availability and supply chain for HTS magnets which depend on various rare earth elements – which are expensive and primarily sourced from China should be further assessed. In particular, because two fusion start-ups, as well as some public programmes, are now pursuing tokamak using HTS magnets.
8.5. Recommendations for future work

Recommendations for future work are aligned with the limitations detailed in 8.4 as a means to address them.

8.5.1. On fusion innovation

None of the fusion start-ups mentioned in this research has yet achieved commercial fusion. Further, all are only at an early stage of the commercialisation process. Innovation in fusion start-ups – and on the public programme, particularly as the operation of ITER edges closer, and the public programme approach responds to the paradigm shift – will continually evolve as missions progress and companies grow. It is thus recommended that fusion innovation receive greater focus as an area of research. Specifically, contributions from subject matter experts from the research fields combined in this interdisciplinary research would be useful.

Furthermore, noting the lack of quantitative analysis of fusion innovation as discussed in 5.4.4, it is recommended that a quantitative approach to understand innovation and to help navigate the pathway to commercialisation for fusion start-ups is developed. Such research could be used to complement the qualitative research approach presented in the early chapters of this thesis to better understand fusion innovation.

8.5.2. On roadmapping for fusion

The roadmapping process developed for Tokamak Energy should be continually developed and adapted to support the company as it grows and moves forward with its mission. In particular, Tokamak Energy should evolve the process to be better aligned as a planning tool to support its development cycles (to increase agility), explore how to use SRLs and IRLs as a metric for technology development for commercialisation, in addition to TRLs.

Similarly, even though strategic milestones inherently provided the key steps in the commercialisation process for Tokamak Energy, they do not account for the wider commercial (market) environment. A markets layer should be developed and integrated into the existing roadmap to ensure the programme considers commercialisation more explicitly – which should have been incorporated earlier in the process. To facilitate this, the process to adapt the existing roadmap and process to include a markets layer, including specific tools, is detailed in 5.4.1.2.1. Further, an aggregated approach to measure overall innovation readiness, considering both technical and commercial readiness, could be adapted to the existing framework, as outlined in 5.3.5.2.

The roadmapping process developed in this research is a case study on a single fusion start-up. The process could usefully be applied to other fusion start-ups as well as to other
start-ups pursuing missions that are high-tech and involve hardware-based agile innovation. In addition to the space exploration sector, the process could be usefully applied to, e.g. the biotechnology sector (see (Singer & Bonvillian, 2017; Usman & Vanhaverbeke, 2017)).

It is recommended that a sector-level (or “industry-level”) roadmap be developed to support understanding of the overall fusion industry, as existing roadmapping processes in support of public fusion programme are limited in scope (see 3.4.2). Whilst the process developed in this research is for fusion start-ups, the core aspects could be used to support the development of an industry-level roadmap. Naturally, however, such a task should be conducted by an international and independent group that can consider all the elements, challenges and players that exist in the wider fusion innovation ecosystem. It would result in a broader understanding of fusion innovation, including – for example – a better view of potential commercial pathways for the industry.

8.5.3. **On natural resources for fusion**

A deeper analysis of the potential policy challenges associated with the commercialisation of D-T fusion should be carried out. Such research should necessarily be conducted by an independent organisation to ensure objectivity because the outcomes of such research will affect all D-T fusion endeavours, public and private. Accordingly, governments and other governing organisations such as the IAEA should be involved as they are positioned to analyse policy issues such as regulation, proliferation, and export control.

Fusion start-ups should make use of available CANDU tritium for experiments whilst it is available (see 6.3.5.3). At the same time, based on the “blanket innovation space” identified (2), commercially viable tritium breeding blanket designs should be developed.

8.6. **Reflection: is fusion still 30 years away?**

The final section of this thesis is used for the PhD researcher to briefly provide personal reflections on the research. The question raised in the STIM workshop relating to timescales to fusion (see 5.2.2.5) is discussed in 8.6.1. Subsequently, whether the pathway to commercial fusion can be accelerated is contemplated in 8.6.2.

8.6.1. **On timescales to fusion**

A common criticism of fusion start-ups is the timescales on which they hope to achieve commercial fusion. Many fusion start-ups are targeting fusion power breakeven around 2025 or sooner, and it is these targets that often come under scrutiny. There two reasons why fusion start-ups setting and publicising these timescales are important and justified, which shall be briefly discussed:
1. Fusion start-ups are targeting ambitious timescales which represent a best-case scenario which functions to spur development and to gain investment.

2. It is what future targets (milestones) will achieve that is more important than the timescale upon which they are achieved.

Fusion start-ups are typically driven by investor-set targets, presented in this research as strategic milestones. These milestones are used to mark progress and to move onto the next stage of development. To achieve the fusion power breakeven milestone, and milestones leading up to it, fusion start-ups have identified and planned the broad technology development steps required – with the support of roadmapping in the case of Tokamak Energy. The current plan – as shown in the Tokamak Energy communications roadmap, for instance – shows the fastest possible route to overcoming technology challenges towards that milestone. To achieve that plan requires investment and the perfect development, building and testing of technology. In other words, the investment must be provided post-haste so that resources, i.e. workforce, machinery, equipment, laboratory space etc. can be scaled-up without delay. In parallel, technology development must proceed without any unknowns or obstacles. Any delay, lack of resources or technology challenge will thus affect the capability to achieve that milestone. As such, timescales should be considered as more than simply aspirational, but they should not be viewed as a project plan (see 5.6.1.3). Instead, they represent a view of the desired future which is plausible if no setbacks occur, i.e. if all unknowns – Rumsfeld’s famous quote regarding “unknown unknowns” is apposite here – are ineffectual or have already been identified; and if sufficient investment is made, then – and only then – can these timescales be plausible. Naturally, unknowns on the future path will lead to setbacks – or perhaps breakthroughs – that will change the trajectory or the speed of progress. Given the improbability of a best-case scenario, the reality is that current timescales will be pushed back. However, publicising high-level plans and timescales will draw interest from investors, and – with the support of a roadmap – can show that the plan is ambitious but plausible, which is necessary to deliver on it.

Parallels with SpaceX can again be drawn. In 2018, SpaceX outlined goals for a manned mission to Mars by 2024. It acknowledged that it might not achieve this goal, and even acknowledged that they are unsure exactly how they will achieve this goal (see (Rigby, Sutherland & Noble, 2018)). However, the company had outlined the vision and the steps to get there and – via an agile approach in which ideas and technologies are tested, even if imperfect or not well understood – it is now focused on demonstrating progression towards their goal. This approach may not yield a manned mission to Mars for SpaceX in 2024. However, it is the targets themselves that are ambitious, which spur development and can drive investment. Even if the fastest possible route is not achieved – similar to the timescales published by several fusion start-ups – setting ambitious targets that are
narrowly missed but in which progress is being continually made, can still be fast. The same can be true for fusion start-ups.

8.6.2. Accelerating the pathway to commercial fusion

Finally, the central theme of this thesis is focused on the pathway to commercialisation. The topics explored that relate to this central theme are the approach to innovation – and thus commercialisation – by fusion start-ups, roadmapping as a method to support the development of a pathway to commercialisation, and the understanding of key challenges associated with natural resources that may limit or slow commercialisation. One question not addressed is: what is the optimal pathway to achieve commercial fusion? This is difficult to answer, but a question that is arguably more important is: can fusion be commercialised soon enough to address current energy problems facing humanity? This thesis has provided insights that indicate that the length of time to any real market impact for fusion technology could be substantial – even if it can be accelerated. In particular, even if fusion technology were to be “ready” by 2035, the fusion industry will need investment and time to scale up, and the number of reactors that must be built to address the current energy issues – which, as noted in this thesis, extend far beyond the decarbonisation of electricity – is unknown. Therefore, even on the fastest timescales, it is unlikely that fusion would become a game-changer to address the current energy problems unless it offered a wholly unique solution. It is contended that due to the problems with D-T fusion, some of which have been broached in this thesis (e.g. waste from blankets, potential concerns over proliferation, cost), there may be a need to move towards fuel cycles that do not require tritium, e.g. D-\(^3\)He. A fusion reactor that does not rely on a D-T fuel cycle could be truly disruptive. At the back-end of the innovation process, i.e. the commercialisation phase, fusion start-ups must look to markets other than electricity. Fusion has the capability to solve problems that cannot be tackled by renewables and that are not favourable for conventional nuclear technology, such as hydrogen generation or the direct supply of energy in the form of heat. It is these markets that might present a better commercial pathway.

In any case, however, the shift to alternative fuel cycles and the focus on non-electricity applications do not change most of the focus of near-term fusion development programmes. As such, these insights do not change the overall direction of travel for current fusion R&D. In other words, the goal still remains to first realise fusion’s Wright Brother’s or “man on the moon” moment. Beyond this, whilst it is not possible to definitively answer whether fusion is still 30 years away (or sooner), fusion start-ups do have an opportunity to accelerate development and to carefully consider the next steps to commercialisation, using – amongst many other factors – the contributions from this thesis to support them in that mission.
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Appendices

Appendix A-1  Example of a TGI file (TGI #12 for Tokamak Energy) used to capture information as part of the roadmapping process.
Objective & Definition

Fusion reactors must breed their own tritium from a lithium-based breeding blanket. To ensure net positive tritium production, a blanket must be designed to produce and extract tritium, as well as turn neutron energy into usable energy. Dedicated design for a spherical tokamak is needed, as e.g. a spherical tokamak does not allow breeding in the central column due to space restrictions, and as such tritium breeding will impact minimum device size.

Content (what are the challenges, what is missing, is more information needed?)

- Example:
  - External tritium supply to make up for lack of a breeding blanket is an issue
  - Must consider future blanket design options and choose a breeding blanket concept

Methods of Resolution

- Example:
  - Watching brief on Laboratory X
<table>
<thead>
<tr>
<th>Resource considerations</th>
</tr>
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<tbody>
<tr>
<td>Example:</td>
</tr>
<tr>
<td>o Allocate £XXX to a study on blanket technology for spherical tokamaks</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Candidates for Ownership</th>
</tr>
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<tbody>
<tr>
<td>Example:</td>
</tr>
<tr>
<td>o Allocate TGI to engineering manager with support of expert consultant</td>
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<table>
<thead>
<tr>
<th>Actions &amp; Recommendations</th>
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<tbody>
<tr>
<td>Example:</td>
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<tr>
<td>o Identify key collaborators</td>
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</tbody>
</table>

<table>
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<tr>
<th>High-level linkages to Other Gap Issues</th>
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</thead>
<tbody>
<tr>
<td>Example:</td>
</tr>
<tr>
<td>o #4 ports for diagnostics reduce the space available for tritium breeding</td>
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</tbody>
</table>
Appendix A-2

Agenda for workshop 2 at Tokamak Energy.
<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0830 – 0850</td>
<td>Introduction and foreword by Tokamak Energy CEO</td>
</tr>
<tr>
<td>0850 – 0900</td>
<td>Changes to the roadmap and process since last workshop</td>
</tr>
</tbody>
</table>
| 0900 – 1030| Review of Technology Gap Issues. Starting with high-leverage Gap Issues (Energy Confinement – TGI #1, HTS Magnets – TGI #5, Divertor – TGI #6, Inner Radiation Shield for Central Column – TGI #7), for each:  
- Check content. What is missing? What needs more detail?  
- What are the methods of resolution?  
- Who are potential collaborators?  
- Who are the candidates for ownership?  
- What are the resource needs?  
- What are the actions / recommendations?  
  Method or working will be part break-out in small groups and part plenary |
| 1030 – 1045| Coffee break                                                                                                                             |
| 1045 – 1200| Review remaining Technology Gap Issues                                                                                                   |
| 1200 – 1215| Actions / recommendations for Technology Gap Issue progress and Roadmap development                                                       |
| 1215 – 1230| Reflection on the workshop and pathway ahead by Tokamak Energy CEO                                                                     |