WECD
Warwick Economics & Development

Cryogenics Impact Report

March 2015

A Report for the

Science & Technology Facilities Council

Acknowledgements

As part of this Cryogenics Impact Review, a series of consultations were conducted with various stakeholders. We would like to express our thanks and appreciation to the following people for their input into this review.

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Dearman Engine: Michael Ayres
Oxford Instruments: Ziad Melhem
Shakespeare Engineering Ltd.: John Everard
Siemens Magnet Technology: Ian Wilkinson
Sumitomo: Trevor Miller
Thames Cryogenics: David Cooke
University of Southampton: Wendell Bailey and Thom Bostock

Other consultees

Oxford Brookes University
Oxfordshire Local Enterprise Partnership
European Space Agency

In addition, reference has also been made to material contained in the Programmatic Review submissions, with kind permission from: University of Cardiff (Herschel-Planck), the University of Cambridge (Planck), University of Sussex (CryoEDM), Imperial College (eEDM) and UK ATC (JWST and MIRI).

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Executive summary

Cryogenics is an enabling low-temperature technology rooted in the application of physics and thermodynamics. The UK has a particularly strong cryogenic academic, science and business community established over the last 60 years.

This study has shown that this community delivers substantial economic impact to the UK economy, engages in scientific and industrial collaborations and partnerships that are further advancing science and building the UK's international reputation in scientific and technological excellence, and contributes to improving UK companies' competitive position in the global market.

The Science and Technology Facilities Council (STFC) is at the heart of cryogenics research and technology development in the UK. STFC's continuous support and investment in cryogenics has been instrumental in this success; in particular the early development of novel technology that private investors often consider too commercially uncertain to invest in. STFC's wide-ranging cryogenics capabilities include hosting and operating world-class scientific facilities, which help to develop new cryogenics technologies, and providing long-term university partnership programmes to support the scientific community. STFC also leads the UK's contribution to astronomy and space science.

Cryogenics activity in the UK forms a cluster in and around Oxfordshire, with a wide range of economic and scientific activities emanating from the interaction between STFC's Rutherford Appleton Laboratory (RAL), the University of Oxford, and industries ranging from specialist SMEs to global businesses. STFC supports this cluster and other cryogenics work in the UK through the provision of a cryogenics infrastructure at RAL and in other centres, e.g, the UK Astronomy Technology Centre (UK ATC) at the Royal Observatory in Edinburgh and the Accelerator Science and Technology Centre (ASTeC) at Daresbury Laboratory.

Cryogenic systems find application in fields as diverse as food freezing, manufacturing and engineering, medicine and life sciences, satellite applications, astronomy, space exploration, transport and storage of liquefied natural gas, energy (traditional and alternative sources), avionics, defence and security, and in superconductivity. It is therefore unsurprising that cryogenics can be found in approximately 17% of the broad sectors representing the UK economy. More specifically, it is estimated that the total (direct and indirect) GVA[1] contribution of cryogenics-related activities to the UK economy is around £324 million per year. In addition, it is estimated that cryogenics-related economic activities could contribute between £1.6 billion and £3.3 billion to the UK economy in the next 10 years - with STFC, its funded universities and industry all being key players in supporting this growth.

A selection of case studies presented in this report highlight STFC's long-term leadership role in cryogenics-related work in the UK and worldwide, and the resulting scientific, economic and social impacts. Although it has not always been possible to quantify the scale of these impacts within this study, the case studies clearly demonstrate that impacts generated by cryogenics expertise supported by STFC are substantial at UK and international level, thus raising the profile of the UK globally. Examples include:

- **Improving life and health** - STFC has played a major role in the development of superconducting magnet technology, which are used in the majority of today's Magnetic Resonance Imaging (MRI) scanners. This supports 2,200 UK jobs in manufacturing and £137 million GVA as well as savings to the UK economy of over £170 million per year.
- **Expanding future energy sources** - STFC is supporting the development of the Dearman Engine, an engine that by 2025 could potentially deliver total net savings of £113 million, thereby improving UK energy security, local air quality, and reducing carbon emissions by 1,284,000 tonnes. The new engine could also provide a new market for industrial gas producers worth £26 million per year.
- **Championing UK engineering capabilities** - STFC funds and delivers world-class expertise across a wide range of

[1]GVA (Gross Value Added) measures the contribution to the economy of each individual producer, industry or sector in he UK. It is used in the estimation of gross domestic product (GDP), which is a key indicator of the state of the whole economy (http://www.ons.gov.uk/ons/guide-method/method-quality/specific/economy/national-accounts/gva/index.html).

engineering and technologies, working closely with the industry in consultative and collaborative capacities. For example, since the 1970s, STFC and Oxford Instruments have developed a mutually beneficial relationship building on scientific discoveries and their industrial application to create technological benefits for both organisations, and economic and societal impacts for the UK. Specific benefits include superconducting wire and magnets, particle accelerators and cryogenic technology applications. Quantifying and attributing the financial and wider benefits arising from this long-standing relationship are not straightforward, given the number of transactions involved and the lack of comprehensive data that captures all relevant economic activities. Nevertheless, Oxford Instruments executives suggest that this long-standing relationship has generated an additional £100 million in terms of business output.

- **Making space missions possible** - the space industry is a major UK success story, growing to 106,000 jobs and £10.8 billion GVA in 2014. Government support for space science, and for project-build activity in particular, is delivered through the UK Space Agency. STFC is responsible for funding early research and development (R&D) in space science, however, working closely with the space industry helps to ensure that the UK remains competitive in this area. STFC teams have developed different types of cryocoolers for space exploration over a number of years. STFC also provides engineering design and testing of complete cryogenic systems for space missions. Examples include Planck and the Herschel Space Observatory.
- **Monitoring and understanding environmental and climate changes** - cryogenics plays an important role in better understanding environmental and weather-related issues. STFC teams have led and/or contributed to a wide range of UK and international projects including: GHOST, a world-first project to build an instrument for environmental modelling; and Along Track Scanning Radiometers, that provide data on global sea surface temperature, which contributes to our understanding of global warming. Improved weather forecasting through satellite data has been valued at £400 million -£1 billion per year.
- **Leading in ground-based astronomy** - STFC teams are key partners in internationally leading telescopes. For example, the Atacama Large Millimetre Array, with cryostats for the 66 antennae made at RAL and the development of instruments with cryogenic-cooling and cryostat systems for the Very Large Telescope. STFC plays a lead role in developing cryogenic systems for next-generation telescopes such as the European Extremely Large Telescope and the Square Kilometre Array; UK industry is already benefitting from the new contracts arising from these projects.
- **Accelerating global scientific developments** - cryogenics is a fundamental technology for a wide range of scientific facilities including particle accelerators and lasers, with the UK playing a world-leading role, hosting ISIS and the Diamond Light Source in the UK and funding UK access to international research facilities including CERN. The products processed, treated or inspected by particle accelerators globally are estimated to have a collective annual value of more than £312 billion.

In addition to the case studies above, there are a number of potential impacts of cryogenics that could be substantial in the future. STFC scientists follow these developments closely in order to identify future potential for scientific and technological exploitation. Examples include:

- **Rapid Surface Chilling™** - a new cryogenic approach developed by BOC and Bernard Matthews Ltd, which results in reduction of campylobacter counts by 90-95%.
- **Cryogenically-cooled superconducting wind turbine generators** - these could lead to global savings of £9.3 billion, and experiments in the cryogenic-cooling of microchips that could have application in energy, defence and security.

- **Bioenergy** - STFC has already provided support for exploring solutions that would enable the generation and storage of bio-methane for distributed domestic power generation and heating. For the same reasons as for natural gas, liquefying the biogas/bio-methane brings volume and range advantages; and cryogenics plays a significant role in storage and transport of energy sources and, in particular, gases including biogases.

- **Nuclear fusion** - STFC-funded research in terahertz detection systems is being used in the Joint European Torus and at the International Thermonuclear Experimental Reactor in order to help realise fusion as a sustainable world energy source.

- **Quantum technologies** - creating, exploiting, controlling and maintaining the ultra-low temperature environment is crucial for the research and development of quantum-enhanced devices; demand for cryogenics expertise and skills will increase as research in this area intensifies.

Furthermore, STFC cryogenics-related work is resulting in wider benefits to society over and above advancements in research and science, and the creation of businesses, jobs and national wealth. These include:

- **Investment in national skills capabilities** – by offering a critical mass of expertise in key areas and sectors that put the UK at the forefront of scientific exploitation and substantial potential economic gains for UK businesses.

- **Fostering collaborations between research and industry including with SMEs** – through a wide range of support activities, e.g testing facilities, business incubation space, and co-ordination and networking events such as the British Cryogenics Cluster and the Cryogenics Cluster Days.

- **Championing local and regional economic development and inward investment** – the cryogenics infrastructure built around STFC's operations is an important anchor for businesses, their expansion, co-location and inward investment, which is welcomed by both industrialists and scientists.

- **Improving public understanding of science** – STFC teams run a number of public events for schools and the public to build understanding of STFC's work, create a culture in which scientific endeavor is highly valued by society, and inspire young people to follow careers in science.

1. Introduction

1.1. Science and innovation are central to the delivery of economic growth and are acknowledged as the best routes to building long-term national prosperity in a globally-competitive, knowledge-based economy. The UK's seven research councils invest around £3 billion annually in research activities. Among them, the Science and Technology Facilities Council, is one of Europe's largest research organisations, supporting scientists and engineers worldwide. STFC plays a crucial role in this ecosystem by supporting fundamental research and technology that can have short- and long-term impacts, often bringing significant improvements to society.

1.2. Investment in STFC research seeks to understand the Universe from the largest astronomical scales to the tiniest constituents of matter. For 50 years STFC and its predecessors have played a pioneering role in the development of the UK's space, internet and computer animation industries, worth over £500 billion annually to the UK economy. Activities carried out cover a wide range of science, engineering and technology, including materials science, engineering and instrumentation, particle physics, space science, accelerator-based technologies, information technology and computer science. From cancer treatment to airport security, high-tech jobs to hydrogen-powered cars, energy generation to accident-scene emergency care, impact is sought and delivered within and beyond the UK in many aspects of daily life.

1.3. STFC's vision is to maximise the impact of its knowledge, skills, facilities and resources for the benefit of the United Kingdom and its people. In 2010, STFC set out a 10-year strategy to deliver its vision through the three strategic goals of delivering world-class research, world-class innovation and world-class skills. Figure 1.1 sets out STFC's strategic framework to deliver impact for the UK.

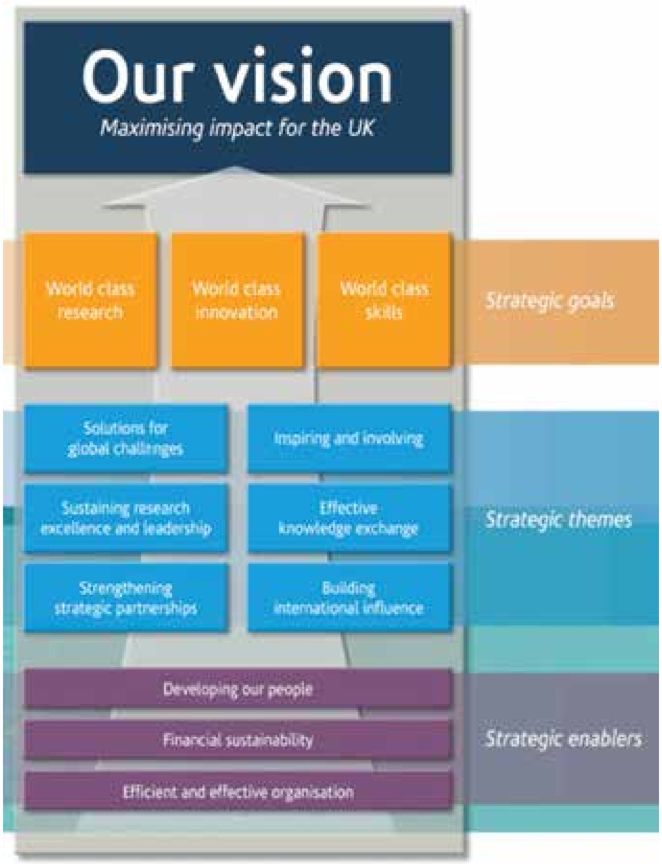


Figure 1.1: STFC's strategic framework to deliver impact for the UK

1.4. Capturing and reporting this impact to stakeholders is a key part of STFC's remit, clearly demonstrating how research, facilities and technology funded by STFC improve everyday lives across the UK.

1.5. It is within this context that this study has taken place and its main aims are:

- to capture the economic and wider impacts of STFC's capabilities and investment in cryogenics; and
- to demonstrate the importance and contribution of cryogenics to the UK economy.

STUDY APPROACH

1.6. As discussed in section 2 of the report, cryogenics technologies cut through and underpin a wide range of sectors including healthcare, medicine, energy, transport, space, food, defence and many others. They bring together and exploit scientific thinking and research capabilities in a variety of areas, and provide unique opportunities for knowledge transfer and the advancement of research. Although relatively unheard of, cryogenic technologies have brought many improvements in our everyday lives, and through commercialisation of research, have contributed to business growth.

1.7. In order to capture the various dimensions of this enabling technology, a combination of qualitative and quantitative techniques has been adopted. These include:

- **Case studies** of STFC's cryogenic capabilities highlighting the impacts and potential in a range of economic activity areas/sectors, combining quantitative and qualitative elements.
- **Quantitative assessment** of direct and indirect economic impacts, as demonstrated by employment and GVA growth. These include assessment of the impact of cryogenic technologies at the UK economy level, and assessment of the impact of companies directly engaged with STFC operations i.e. the cluster activities.
- **Extensive desk-based research** has been conducted to enable mapping out of STFC's cryogenics capabilities and the relationship between activities and projects to various economic activities/sectors and other areas of research. Generic and project-specific information has been collected on the funding, type of funding, area of research, stage of research, key institutions and staff/scientists involved, and on collaborative activity (academic, industry, UK, international, etc).
- **A series of consultations** were also conducted with various stakeholders including:
  - Management/operational research staff at both Rutherford Appleton and Daresbury Laboratories, UK ATC and key personnel within STFC.
  - External stakeholders, scientific and industrial collaborators (academic/industrial/UK and international).

REPORT STRUCTURE

1.8. The remainder of this report is structured as follows:

- **Section 2** presents an overview of cryogenics technologies and UK cryogenics capabilities including the role of STFC.
- **Section 3** provides an assessment of the economic impacts of the technology on the UK economy through the creation of jobs, businesses and the generation of added value.
- **Section 4** provides an overview of wider benefits including benefits arising from the British Cryogenics Cluster Days, skills development and collaborative research.
- **Sector 5** presents a series of case studies demonstrating the impact of the technology on key aspects of life and the advancements of science.
- **Section 6** presents future potential areas for technological exploitation.
- **Section 7** draws conclusions.

2. Overview of cryogenics in the UK

WHAT IS CRYOGENICS?

2.1. Cryogenics is the science that addresses the production, effects and maintenance of very low temperatures. It also includes the study of the properties of materials at cryogenic temperatures. Application of the science takes the form of a classic enabling technology that, over the years, has evolved from its origins in air separation and the liquefaction of gases, into a wide range of applications involving the use of cryogenic fluids and increasingly sophisticated low temperature refrigerators. Cryogenic systems now find applications in fields as diverse as food freezing, medicine, space exploration, transport and storage of liquefied natural gas, energy and defence, as well as in the wide-ranging applications of superconductivity.

2.2. According to the laws of thermodynamics, there exists a limit to the lowest temperature that can be achieved, which is known as absolute zero. Over the years, in terms of the Kelvin scale, the cryogenic region is often considered to be that below approximately 120 K (-153 C)[2]. The most common methods of producing cryogenic temperatures almost always utilise the compression and expansion of gases, thus making these gases valuable 'commodities' in the science and application of cryogenics. Gases such as methane, used at STFC's ISIS facility, argon, oxygen and carbon dioxide can all be supplied as cryogenic liquids[3].

2.3. Cryogenic-cooling of instruments and material samples is usually achieved using liquid helium, or liquid nitrogen. Liquid nitrogen is the most commonly used element in cryogenics and is legally purchasable around the world. Helium is a finite resource on Earth and growing scientific, medical and high-tech demand for helium has been tempered by a doubling of prices over the past five years. In 2014 the price pressure eased for the time being, as substantial new supplies have and will come online in Qatar and Russia by 2020. Nonetheless, prudent high-tech users are adopting helium-smart strategies, such as re-condensing cold heads, to decouple themselves from helium price and supply shocks.

2.4. These issues have encouraged firms such as Siemens to look for substitutes for helium for the future. However, as noted during our discussion with Siemens Magnet Technology, world market leaders in superconducting MRI scanner magnets, "*…At the moment …there is no direct alternative, …moving away from helium dependence requires a completely different technology…and this is a challenge faced across the sector*".

STFC CRYOGENICS CAPABILITIES AND INVESTMENTS

2.5. STFC offers a critical mass of cryogenics expertise and is continuously investing in enhancing these capabilities, which are wide-ranging, as demonstrated by the capabilities of its various research groups and centres at RAL and elsewhere in the UK shown in Figure 2.1.

2.6. Due to the number of groups within STFC engaged in cryogenic activity, this diagram is indicative of the major groups within each department, showing the breadth and types of activity, rather than being truly representational. Other departments such as the programmes department providing university research and R&D funding, the business and innovation department and the international group also support cryogenics-related projects.

[2] NIST (National Institute of Standards and Technology, USA) – (http://www.cryogenics.nist.gov/AboutCryogenics), first published in the MacMillan Encyclopedia of Chemistry, New York, 2002 written by: Dr. Ray Radebaugh of NIST's Cryogenic Technologies Group.

[3] http://www.boconline.co.uk/en/sheq/gas-safety/gas-risks/cryogenic-gas-risks/cryogenic-gas-risks.html

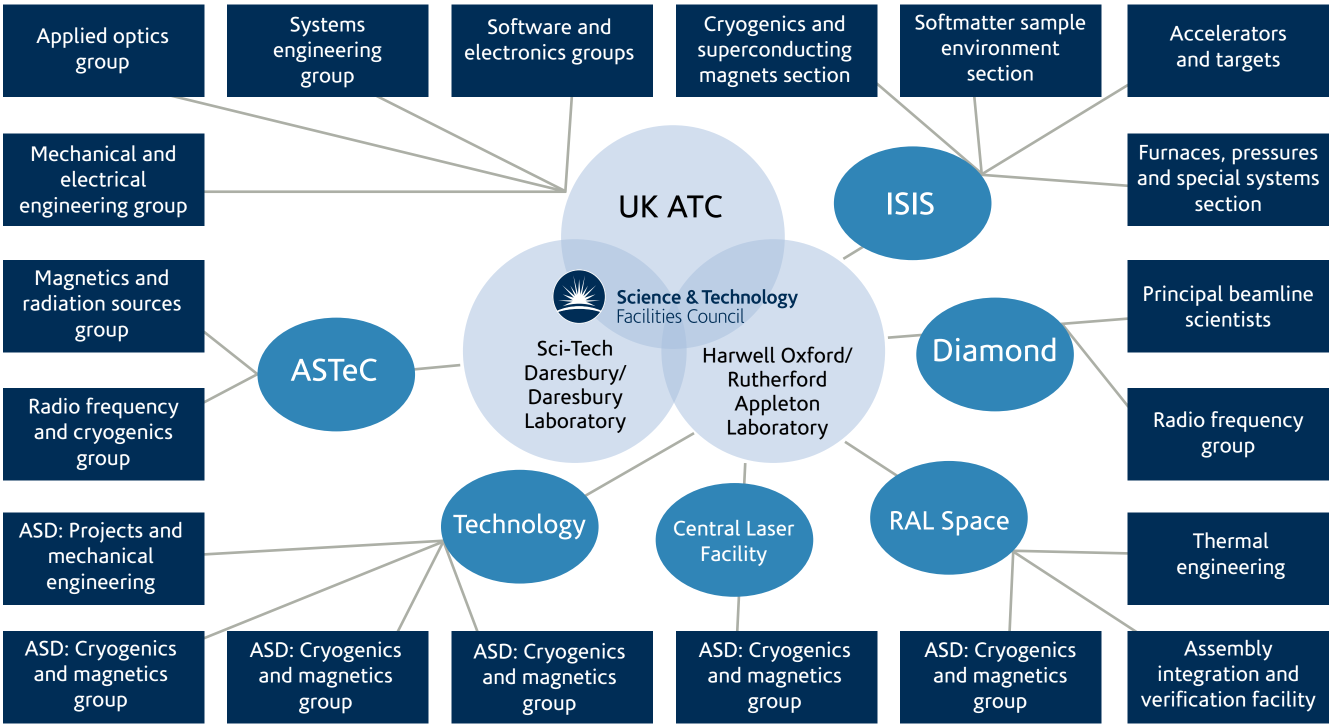


Figure 2.1: STFC cryogenics capabilities, Source: STFC

2.7. A summary of the capabilities of key relevant groups and centres is presented below and more detail about their specific involvement in cryogenics-enabled and related scientific research and applications is provided in section 5 of this report.

- **The cryogenics and magnetics group** (Applied Science Division) is engaged in a wide range of activities in the areas of long life closed cycle cooling systems for spacecraft, superconducting magnet design and manufacture, cryostat design and manufacture and medical applications of cryogenics. Thirty years ago, the group developed the internationally-renowned 10K closed cycle Stirling Cooler for space use. Some recent projects include the development of a cryo-probe for the ablation of cancer tumours and the development of undulators for particle physics and light sources. The group is heavily engaged in the Muon Ionisation Cooling Experiment (MICE) project.

- **The composites and materials testing group** (Applied Science Division) has facilities and expertise in the manufacture and testing of materials in extreme environments, particularly adhesives and composites for cryogenic applications and in high ionizing radiation. A suite of mechanical and thermal testing equipment is used to support STFC's projects as well as the group's in-house technology development e.g manufacture of superconducting magnets.

- **The UK Astronomy Technology Centre** (UK ATC) is the national centre for astronomical technology operated by STFC. It specialises in designing and building instruments for many of the world's major telescopes, both on the ground and in space, as well as conducting observational and theoretical astronomical research. UK ATC research and technology delivers a range of practical benefits, such as monitoring the Earth's environment from ground and space. Often commissions require highly specialised engineering such as high vacuum and cryogenic systems, and cryogenic mounting of optics.

- **The Accelerator Science and Technology Centre** (ASTeC) was created in 2001 as a Centre of Excellence for the study of the production, acceleration and delivery of charged particle beams. It now carries out R&D programmes studying all aspects of the science and technology of charged particle accelerators, ranging from large-scale international and national research facilities, through to specialised industrial and medical applications. New generation particle accelerators, for example, free-electron lasers or linear colliers, are based on superconducting radio frequency technology that requires large helium refrigerators.

- RAL Space represents a national science-led, technology-enabled resource for the benefit of the whole of the UK space community, with many (over 150) collaborations with academia and industry. This resource includes the provision of top-class space and ground-based facilities and environmental test facilities developed to meet the exacting needs of people involved in the design, manufacture and qualification of space hardware. RAL Space has a specialist capability in cryogenic engineering for space projects.
- STFC operates or hosts world-class experimental facilities for the benefit of academic and industrial users, including the **ISIS** pulsed neutron source and the Central Laser Facility, both in the UK. It is also the majority shareholder in Diamond Light Source Ltd, also in the UK. Specialist cryogenics teams support these facilities, both in the successful running of the facilities but also in ensuring cryogenically-cooled sample environments that are required in an increasing number of experiments.

2.8. STFC (and its predecessors) has played a leading role over the years in helping to retain and grow a vibrant and thriving cryogenics community centred in Oxfordshire[4]. This community originates from the interaction between the University of Oxford and STFC's Rutherford Appleton Laboratory (RAL), and a cluster of cryogenics-related research and business activities established around these centres, ranging from specialist SMEs to global businesses such as Siemens Magnet Technology. Oxfordshire's position as the world's leading manufacturer of MRI scanner magnets today can be traced back to pioneering work in superconducting magnet technology at RAL and Oxford Instruments, the University's first spin-out company.

2.9. More specifically, the establishment of cryogenic capabilities in Oxfordshire goes back to the 1930s/1940s. In the 1930s, with the support of Frederick Lindemann, Head of Clarendon Laboratory (part of the Physics Department at the University of Oxford), low temperature work really took off in the Clarendon Laboratory, as did work on magnetic fields. The legacy of all this activity has spilled over into Oxfordshire and elsewhere. Some of the key developments that followed included:

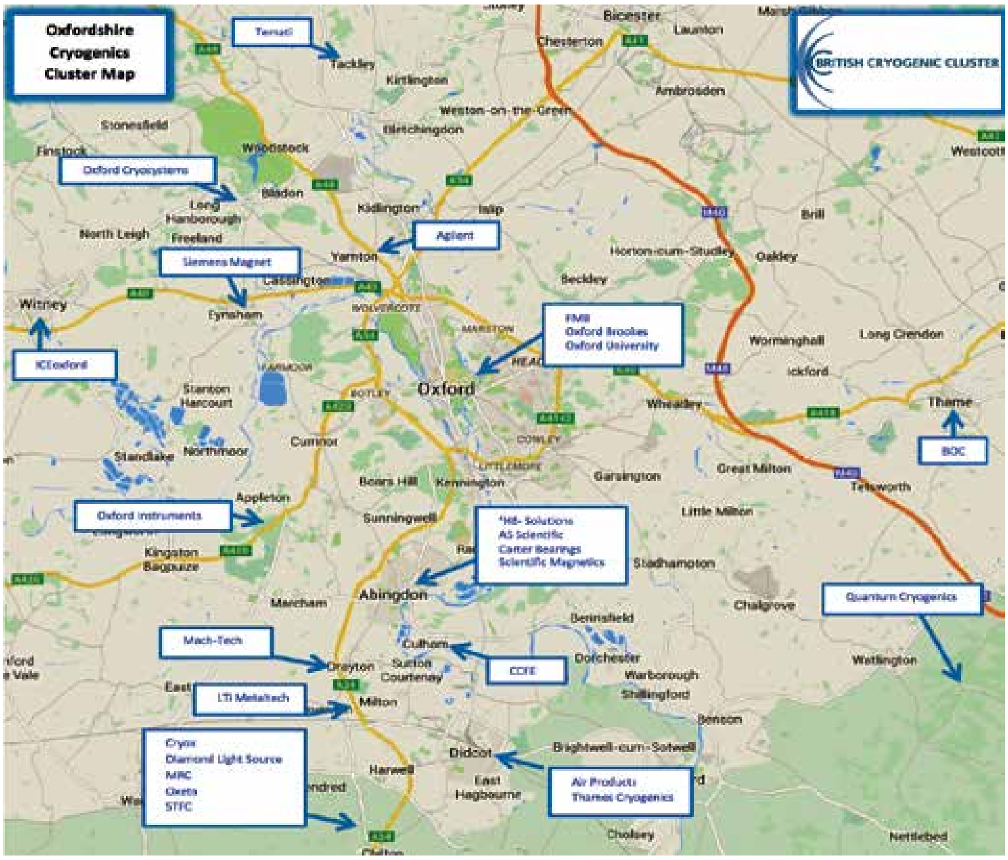
- Oxford Instruments, the University of Oxford's first spin-out company, founded by Sir Martin and Lady Wood in 1959 – with the history of the company documented by Lady Audrey Wood[5].
- Professor Ralph G. Scurlock founded the Institute of Cryogenics, University of Southampton, in 1979.
- Dr Jeremy Good set up Cryogenic Ltd – one of the leading suppliers of high field superconducting magnets and low temperature measurement systems that operate with and without liquid helium. It was set up in 1993.
- Kurt Alfred Georg Mendelssohn, author of 'Progress in Cryogenics' (1906-1980), founded the journal, *'Cryogenics'*.
- John Cosier co-founded Oxford Cryosystems in 1985 with Professor Mike Glazer (Emeritus Professor, Department of Physics at University of Oxford) – the company specialises in cryostats, software and accessories for X-ray crystallography.

[4] It is recognised that whilst Oxfordshire has the strongest research and industry links with cryogenics, there are other areas of expertise in the UK. For example, the Institute of Cryogenics at the University of Southampton established as a research institute in 1979, has been actively engaged in fundamental and applied research in cryogenic engineering and superconductivity for the last 30 years. The Institute has experts in cryogenic systems, thermodynamics and cryogenic coolers, cryogenic safety, handling of cryogen and enhanced heat transfer, and superconducting materials and applications. Additionally, in 1982 the Cryogenics Advisory Unit was formed within the Institute to develop close links with industry and other institutions and to offer R&D, Testing and Consultancy services on a commercial basis. In July 2013, the University of Birmingham also won a £6m grant from EPSRC to create a new Centre for Cryogenic Energy Storage. 'Liquid air' technology could revolutionise the storage of energy, reducing the costs of integrating intermittent generation into the electricity system and ensuring power is available when it is most needed. The new Centre, which will be housed on the University of Birmingham's campus, will be the UK's first dedicated research facility for energy storage using cryogenic liquids, comprising new laboratories, state-of-the-art equipment, and a major demonstration plant.

[5] Magnetic Venture: The Story of Oxford Instruments by Audrey Wood.

2.10. The formation of Oxford Instruments was followed by the establishment of other cryogenic companies in Oxfordshire (often set up by ex-Oxford Instruments employees) including companies such as Thor Cryogenics, Magnex (ElScint) in Berinsfield, AS Scientific in Abingdon, OMT in Eynsham (which morphed into Siemens Magnet Technology), Thames Cryogenics in Didcot, Scientific Magnetics in Abingdon, ICEoxford and Cryophysics in Witney. The map in Figure 2.2 provides an overview of the Oxfordshire Cryogenics cluster (2014).

Figure 2.2: Oxfordshire cryogenics cluster [6]



2.11. This exceptional community made it an obvious choice for a bid in the UK Government's 'National Cluster Mark Competition' in 2010, and from there the British 'Cryogenic Cluster' was formed, subsequently synchronising its membership with the British Cryogenics Council. STFC hosts the British Cryogenics Cluster that fosters collaborations between research and industry, and is also a strong advocate for the new Centre for Applied Superconductivity in Oxford.

2.12. STFC also has university partnership programmes in the fields of astronomy, particle physics and nuclear physics, and for associated technology development, and knowledge exchange. STFC's long-term partnership working is with some of the UK's leading centres in these areas, some specific examples of cryogenics-enabled research and applications include:

[6] Provided by the Oxfordshire Local Enterprise Partnership via the British Cryogenics Cluster (http://bcryo.org.uk).

- **Electric dipole moment (EDM)**. Many projects to measure elementary particle EDMs have been undertaken since 1950. STFC has supported two projects with very strong synergies, the Cryo-neutron EDM (Cryo-nEDM) and the electron EDM (eEDM). These projects have both achieved worldwide scientific interest and are underpinned by knowledge exchange at a global level. For example, the Cryo-nEDM located at the Institut Laue-Langevin (ILL) in Grenoble, was initially an STFC-funded collaboration between RAL, the universities of Sussex, Oxford and Swansea, and Kure (Japan). Similarly, Imperial College has led the eEDM experiment for more than 15 years[7] . This world-leading programme has developed technologies that can provide applications in quantum physics[8]. Research on EDM projects seek to understand why the Universe is made of matter rather than anti-matter - one of the big mysteries facing particle physics and cosmology today. It also complements STFC- supported particle physics work in this area.
- **The cryogenics group at University College of London.** Part of the Mullard Space Science Laboratory. One element of the group's current £2 million STFC-funded research programme (2014-2016) sets the foundation for the exploitation of future space missions including Gaia, James Webb Space Telescope (JWST) and Solar Orbiter, and much of their work is in conjunction with industry e.g. e2V and Astrium. One current STFC-funded project is the 50mK cryogen-free system for cooling an array of sensors for the European Space Agency (ESA)'s new, large X-ray observatory called ATHENA[9].
- **Durham University.** STFC is providing £7.4 million[10] research funding for astronomical research at Durham University, between 2014-17. The team at the Centre for Advanced Instrumentation working with Surrey Satellite Technology Limited (SSTL) contributed to a 3D spectroscopy instrument for the JWST, which will provide a type of advanced imaging, designed to detect the light from the first stars and galaxies that formed in the young Universe. The instrument was built under contract to Airbus for ESA. Durham university also have a superconductivity group that has built a number of specialist probes for making strain, magnetic, resistive and optical measurements on superconductors.
- **Astronomy Instrumentation Group (AIG) at Cardiff University.** The combination of high sensitivity and fast speed of response for THz[11] (terahertz) detectors requires a technology that is cooled to cryogenic temperatures. STFC and its predecessors have provided research funding[12] of more than £10.5 million over 13 years, enabling AIG to become a recognised world-leader in the design, manufacture and integration of THz technology. Commercialisation of this unique THz detection systems technology by the group's spin-out company, QMCI Ltd, has achieved global sales resulting in significant revenue being generated. Third parties in the alternative energy and security markets use exploitation of AIG's technology. Examples of these include fusion diagnostics for the Joint European Torus – the largest magnetic confinement experimental nuclear fusion facility in the world, with the primary focus on achieving fusion as the sustainable world energy source, and the International Thermonuclear Experimental Reactor project, which is currently building the world's largest experimental tokamak nuclear fusion reactor[13].

[7] Results were published in Nature.
[8] EPSRC-funding is supporting the next major technological advance in eEDM measurement.
[9] ATHENA is ESA's Advanced Telescope for High ENergy Astrophysics mission http://sci.esa.int/ixo/48729-about-athena/
[10] http://star-www.dur.ac.uk/
[11] The terahertz is a unit of electromagnetic (EM) wave frequency equal to one trillion hertz (1012 Hz). The terahertz is used as an indicator of the frequency of infrared (IR), visible, and ultraviolet (UV) radiation.
[12] STFC funding has been provided through an STFC Innovations Partnership Scheme award.
[13] http://results.ref.ac.uk/Submissions/Impact/1638. At the Geneva Superpower Summit in 11/1985, following discussions with President Mitterand of France and PM Thatcher of the UK, the then General Secretary Gorbachev of the former Soviet Union proposed to U.S. President Reagan an international project aimed at developing fusion energy for peaceful purposes - the ITER. The initial signatories of the former Soviet Union, the USA, the European Union (via EURATOM) and Japan, were joined by PR of China and the Republic of Korea in 2003, and by India in 2005.

3. Economic impact of cryogenics in the UK

MEASURING THE IMPACT OF AN ENABLING TECHNOLOGY

3.1. Assessing the economic impact of a sector or an industry[14] in the UK requires bringing together the following effects:

- **direct impact:** persons employed directly by the sector and receiving wages and salaries;
- **indirect impact:** income and employment created in businesses which supply the goods and services used by this sector in its day to day activities; and
- **induced impact:** further income and employment generated as wages created directly and indirectly are spent within the economy.

3.2. In general, estimating an industry's size and its impact in the UK economy is a relatively straightforward exercise. A sector or an industry consists of a critical mass and group of relatively well-defined economic/business activities around a distinct primary activity (processes and products). Sectors and industries are therefore defined by the product and the economic activities taking place around them (ranging from R&D and technology to manufacturing, sales and trading and healthcare/services), and by their 'size' in terms of business operating in these activities, number of people employed, supply chain affected and output generated.

3.3. Assessing the economic impact of enabling technologies, however, poses a few methodological challenges. Enabling technologies achieve their economic impact through two principal channels:

i) *enabling* another technology to happen or a user to perform a task – as intended or by empowering productivity improvements and advancements; and

ii) through *disrupting* a status quo, by introducing new ideas, processes, and products (i.e. essentially inventing or innovating) and thus constructing new ways in terms of how things are done and, potentially, of how we live and work.

Assessing the economic impact of the former is not a straightforward exercise, as it requires isolating and quantifying the extent of the significance of a particular technology in an often highly interdependent process, whereby a combination of human, capital and technological resources 'work together' simultaneously to deliver a final output. Assessing the economic impact of disruptive technologies faces more methodological challenges given the early uncertainties involved in relation to their application and commercialisation. The earlier the stage of the technology development, the more assumptions need to be made in relation to its applications and impact on economic activities. Therefore, assessing economic impact at an early stage of a technological development can be regarded as a predictive exercise. Nevertheless, such findings cannot be ignored, as waiting until these technologies exert their impact on the economy would mean that it might be too late to capture and capitalise on their full benefits.

3.4. In order to capture both the enabling and disruptive aspects of cryogenics, a combination of methods has been deployed for this study. A mainly quantitative approach has been followed to capture the economic impact of the enabling technology. The findings of this approach are presented in this section of the report. These are complemented by a series of case studies illustrating STFC's key role in cryogenics-related activity and demonstrating both the application of the technology in specific sectors to date and its role in the advancement of research and potential applications. These are described in section 5 of the report.

[14] The terms industry and sector are used interchangeably. However, a sector refers to a larger part of the economy than an industry; sectors are broken down into industries.

ESTIMATING THE ECONOMIC IMPACT OF CRYOGENICS AND STFC'S INVESTMENTS IN CRYOGENICS

3.5. In order to establish the economic coverage of the technology, a number of tasks were undertaken:

- **Review of sectors currently involved/involving cryogenics** based on companies and organisations currently engaged with the British Cryogenics Council (BCC), published material and discussions with scientists and selected companies currently involved with cryogenics, in order to establish the extent of current/desired coverage: upstream sector activities (e.g research, manufacture), downstream sector activities (e.g services), supply chain, enabling products and technologies.
- **Exploring fitness with UK Standard Industrial Classification (SIC)** - although SIC systems have their limitations (SIC systems are hierarchical systems for defining what a company does, focusing on their principal activity rather than the type of business they are engaged in and/or the technologies they deploy), nevertheless, they can be used as a starting point to broadly profile a sector and access a wide range of published benchmark data that can position the sector in context with the rest of the economy and can make it relatively straightforward to track data on an on-going basis. Using the SIC definitions, the following key sectors involving/involved in cryogenics (2-digit) were identified:

SIC 2007 Sector codes

6	Extraction of natural gas
9	Mining support services
16	Manufacture of wood products
20	Manufacture of chemicals
21	Manufacture of Pharmaceuticals
22	Manufacture of rubber and plastics
25	Manufacture of fabricated metal products
26	Manufacture of electronics
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment
30	Manufacture of transport equipment
32	Other manufacturing
33	Repair and installation
35	Gas Supply
42	Civil Engineering
43	Specialised Construction Activities
46	Wholesale trade
64	Financial Services
70	Activities of head office
71	Engineering and Testing
72	Scientific Research
74	Other professional activities

- **Estimates of current and potential market share of cryogenics-related applications in the identified SIC sectors**, verified through discussions with key industry stakeholders.

- **Identification of additional companies in the UK that are involved in cryogenic-related activities.** SIC codes alongside key search words were used to identify additional companies carrying out activities similar to those with which BCC are involved. Company information, e.g employment and turnover, was drawn from a commercial business database (Bureau Van Dijk/FAME).

- **Review and analysis of 2010 UK input-output (I-O)** data in order to establish indirect/ intermediate demand and employment data. An indirect multiplier of 1.91 was established. This was based on the 2010 UK I-O multipliers for each of the SIC sectors within which businesses operate. The total figure is therefore a blended rate that represents the share of the different SIC sectors that comprise the cryogenics sector. The most significant sectors are the manufacture of machinery and equipment, gas supply and the manufacture of chemicals.

- **Development of future growth scenarios for the technology for the next 10 years**, drawing upon different sources of data as follows:

  - A low growth scenario of 3% - based on the UK Treasury medium term consensus forecasts.

  - A medium growth scenario of 8.5% – based on estimates of growth in chemicals, health care and medical (www.companiesandmarkets.com).

  - A high growth scenario of 16.40% – based on growth forecast for the superconductor sectors (BCC Research at www.bccresearch.com).

- **Other assumptions made:**

  - Productivity growth rate of 1.33% for the next 10 years – based on the UK average output per hour between 1998-2013.

  - Net Present Value (NPV) discounted 3.5% per annum for the next 10 years as recommended by HM Treasury.

- Furthermore, the **number of individuals directly employed in STFC's cryogenics research and business development activities** has been estimated in order to assess their operational impact on the economy.

3.6. Figure 3.1 summarises the types of impacts that have been explored to provide a full picture of the impact of cryogenics in the UK economy.

Figure 3.1: Approach to capturing the economic impacts of cryogenics in the UK economy

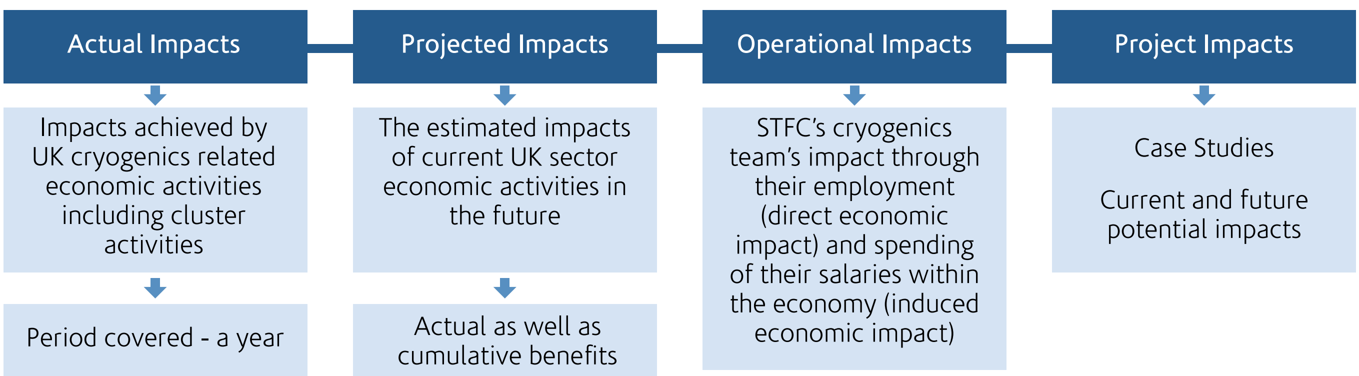
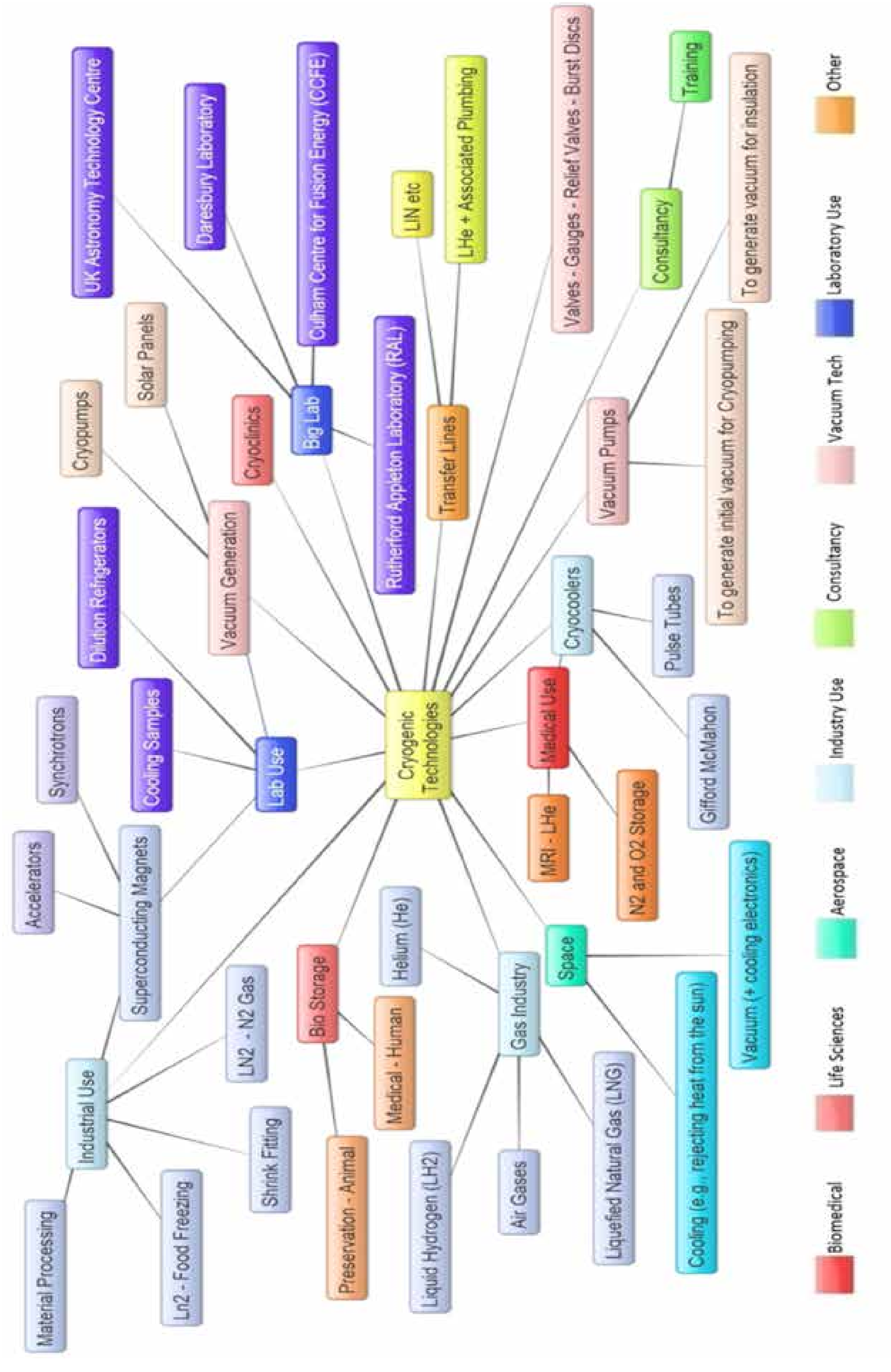


Figure 3.2: The reach of cryogenics



ECONOMIC IMPACT OF CRYOGENICS IN THE UK ECONOMY

3.8. Economic impacts have been estimated for gross value added and employment. An indicative contribution of companies/activities related to the cryogenics cluster has also been estimated.

3.9. As shown in Figure 3.3, it is estimated that:

- Cryogenics-related economic activities directly employ 1,487 employees across the UK (based on 118 businesses in sectors of the economy presented in paragraph 3.6).
- Cryogenics-related employment generates around £170 million GVA for the UK (direct economic impact/2014 figures).
- Taking into account multiplier effects, **the total (direct and indirect) GVA contribution of cryogenics-related activities to the UK economy is around £324 million.**
- Of these, £97 million of direct and indirect GVA are generated by companies/activities directly related to the Cryogenics Cluster (based on 68 companies employing 615 employees).

Figure 3.4: Estimates of annual employment and GVA impacts generated by UK-wide cryogenic activities and cluster contribution

	Estimated number of businesses involved in cryogenics-related activities	Estimated number of employees in cryogenics-related activities	Estimated total direct GVA (£)	Composite GVA multiplier	Total direct and indirect GVA contribution (£)
UK-wide	118	1,487	£169.8m	1.91	£324.3m
Cryogenics Cluster	68	615	£53.4m	1.83	£97.7m

3.10. STFC's cryogenic teams also make a contribution to the UK economy through operational impacts i.e. their employment (direct economic impact) and spending of their salaries within the economy (induced economic impact). It is estimated that 135 FTEs are fully involved in cryogenics-related activities within STFC; their contribution to the UK economy is an estimated £11 million per annum.

3.11. Wider benefits arising from STFC's investments in cryogenics are presented in section 4 of the report. Case studies in section 5 also present impacts arising from project specific STFC-funded activities.

FUTURE ECONOMIC IMPACT OF CRYOGENICS IN THE UK ECONOMY

3.12. As shown in Figure 3.5, projecting the direct impact of cryogenics forward for the next 10 years indicates that **cryogenics-related activities could contribute between £1.6 billion and £3.3 billion to the UK economy in this period, depending on different assumptions made about the growth of the UK economy** and sectors of high relative importance to cryogenics e.g medical, superconductors, manufacturing. As noted in paragraph 3.5:

- A low growth scenario of 3%
- A medium growth scenario of 8.5%
- A high growth scenario of 16.4%

Figure 3.5: Projected GVA impact of cryogenics to 2024 generated by UK-wide cryogenic activities and cluster contribution

	Current GVA	Cumulative GVA (2014-2024) NPV growth scenarios		
		Low	Medium	High
UK-wide	£169.8	£1.6bn	£3.4bn	£4.2bn
Cryogenics Cluster	£53.4	£500m	£700m	£1.1bn

3.13. On the basis of the same assumptions, the level of employment supported by these activities is expected to rise to approximately 6,000 employees in a high growth scenario as shown in Figure 3.6 or to 2,900 employees in a medium growth scenario.

Figure 3.6: Projected employment impact of cryogenics to 2024 generated by UK-wide cryogenic activities and cluster contribution

	Current employment	Future employment to 2024 growth scenarios		
		Low	Medium	High
UK-wide	1,487	1,600	2,900	6,000
Cryogenics Cluster	615	680	1,200	2,500

3.14. Calculations of future potential benefits exclude specific project benefits that arise from the application of cryogenic technologies and the collaboration with STFC, e.g in the form of increased turnover and sales from the commercialisation and exploitation of successful products. Examples shown in section 5 of the report demonstrate how the commercialisation of new technologies provides considerable financial benefits to the end user, i.e businesses and potentially to the economy.

4. Wider benefits

4.1. STFC's engagement in cryogenics-related work is also resulting in wider benefits to society over and above advancements in research and science, and creation of businesses, jobs and national wealth.

Investing in national skills capabilities – STFC offers a critical mass of expertise in key areas and sectors that put the UK at the forefront of scientific exploitation, and enables substantial potential economic gains for UK businesses. The Government recognises that research and innovation, and the skills needed to exploit them, are the essential components that will allow the UK economy to prosper and grow. The Innovation and Research Strategy for Growth and the Annual Innovation Reports all emphasise the importance of knowledge generation by the UK research base and of higher, specific and wider skills development (workforce and researchers) for the improvement of the UK performance globally in terms of both economic wealth and well-being.

STFC's cryogenics capabilities make a significant contribution to this agenda directly and indirectly. Research, technical and business skills deployed by STFC's centres are world-class as demonstrated by the case studies. Many STFC departments such as the particle physics department, ISIS and the cryogenics and magnetics team contribute to significant training of research students, and provide support and general infrastructure for university groups. Each summer, students are also offered placements.

Skills developed with the support of STFC's investment in cryogenics-related expertise also indirectly support other key sectors of the UK economy. Skills for space-related technologies are transferrable and useful for the aerospace and defence industries and STFC is a major contributor to current and future employment in this area. Support is provided through technical activities at STFC's UK Astronomy Technology Centre, RAL Space and the technology department at RAL. Additionally, STFC's Harwell Oxford Campus is home to the Harwell Space Cluster. In order to develop the Cluster, Innovate UK invested £1 million in 2014 to encourage high-growth companies to develop innovative projects that could achieve commercial success. STFC is the Cluster Champion for Innovate UK's Harwell Space Launchpad[15], working closely with companies in and around the Harwell Space cluster.

In general, the role of STFC in supporting the generation of higher level, but also intermediate, technical skills and expertise in cryogenics-related areas is particularly valuable, considering that trying to source specialist cryogenics expertise is difficult. It needs to be acknowledged that this shortage in the market poses a challenge for STFC centres and facilities in terms of retaining and attracting of relevant talent, given that the private sector may be able to offer more competitive remuneration packages. Therefore, STFC is fulfilling a key role in the cryogenics industry through its continuous support.

Fostering collaborations between research and industry including with SMEs – STFC offers a wide range of support through testing facilities, business incubation space, and co-ordination and networking events such as the British Cryogenics Cluster. Each year, the Cluster hosts a Cryogenics Cluster Day at RAL comprising a mix of seminars, trade shows and laboratory visits. These free-to-attend events for delegates are highly appreciated by industrialists and scientists alike.

As stated by one of the companies participating in this study:

"It [the British Cryogenics Cluster] gives a wider structure in which to operate, support, exchanging experience etc. [The cluster network] also provides an understanding of what issues are coming up in the cryogenics industry, such as regulatory and legislative changes, which is important for us. The cluster base also provides a platform for lobbying – for example, a few years ago during the helium crisis, the cluster

[15]The Launchpad initiative is an Innovate UK initiative that supports business groups, suppliers and associated institutions who work together in the same location (https://www.gov.uk/innovation-get-details-about-innovate-uk-funding-competitions).

contacts were able to raise awareness of this, and of the importance of helium supply to the industry, through the media etc, and following the shortage, producers concentrate more on forecasting provision levels, and taking a longer term view, which was a positive outcome."

For another company:

"The cluster is very important…The UK has lots of expertise in cryogenics, often we are not that good at pulling everyone together to support it… we haven't met anyone we didn't already know during the days, but that is because it is a small community and we tend to know most people…but having the opportunity to meet, to share ideas is very useful."

Lockheed Martin is to open a space technology office on Harwell Campus as a means of expanding relationships in the space sector. As stated by the company: *"Harwell's open innovation environment, combined with the breadth and depth of the research and innovation undertaken on campus lends itself to the Lockheed Martin collaborative approach, which is already established on other campuses in the United States."*

Most importantly, STFC's testing facilities are available to SMEs and STFC helps to foster small business research and innovation by providing leading-edge laboratory space for high-tech SMEs to improve their efficiency and competitiveness.

Championing local and regional economic development and inward investment – as noted in section 2 of the report, a cryogenics infrastructure has built up around RAL and the other STFC facilities, comprising everything from global corporations to sought-after niche expertise in industry and scientific thinking and advancement. This infrastructure is an important anchor for further existing business expansion and additional inward investment, which would be very much welcomed by both the industrial and scientific world. As stated by one of the companies participating in this evaluation:

"The more high-tech manufacturers in the region, the more they can gear up to support the cluster – precision manufacturing requires a specialist support base."

STFC is also making a significant contribution to the development of the new Centre for Applied Superconductivity in Oxford, working alongside the Oxfordshire Local Enterprise Partnership, local businesses in the sector (Oxford Instruments, and Siemens Magnet Technology), the University of Oxford, cryogenics companies, and end users (including SMEs).

Securing societal well-being and improving the public's understanding of science – the case studies presented in section 5 of this report clearly demonstrate the former of these contributions, e.g, MRI scanning, the Square Kilometre Array and Planck.

STFC also runs a number of public engagement events for schools and the public, with the aim of creating a culture in which scientific endeavor is highly valued by society. Events such as Particle Physics Masterclasses inspire young people to follow careers in science.

Overall, STFC's cryogenics-funded research, skills, knowledge and technology transfer for the benefit of the UK economy and society is considerable. It involves both the supply of skilled staff and university researchers who work with or move into industry and other scientific environments, and also transfer of knowledge, skills and technologies to industry through collaboration activities.

Particle Physics Master Class at Daresbury Laboratory

5. Case studies

5.1. This section provides a selection of case studies that highlight STFC's leadership role in cryogenics-related work worldwide and its resulting scientific, economic and social impacts. Case studies have been put together drawing upon existing documentation and interviews with scientists, academics and industrialists. Although it has not always been possible to quantify the full scale of these impacts, the case studies clearly demonstrate that impacts generated by cryogenics expertise supported by STFC are substantial and global.

5.2. STFC-funded work related to cryogenics covers a diverse range of sectors and areas of world-leading scientific research and application of technologies. The case studies presented here are not meant to provide an exhaustive account of all cryogenics-related research and collaborations funded and supported by STFC over the last 30 years; they represent only a sample of this work in the following areas:

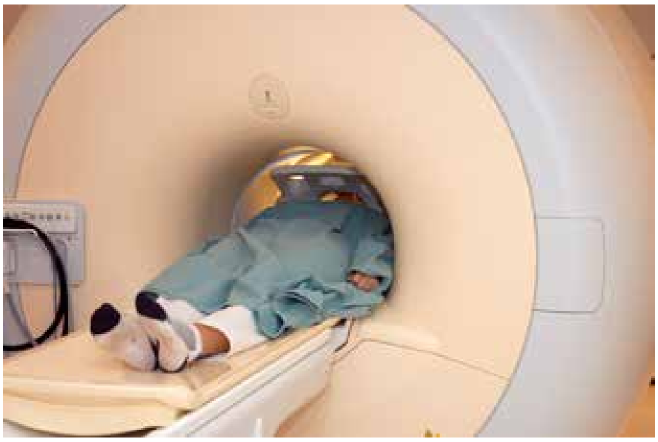
- Improving life and health
- Expanding future energy sources
- Championing UK engineering capabilities
- Making space missions possible
- Monitoring and understanding environmental and climate changes
- Leading in ground-based astronomy
- Accelerating global scientific developments and exploitation

IMPROVING LIFE AND HEALTH

5.3. STFC research has played a major role in the development of **Magnetic Resonance Imaging** (MRI scanners, the major contribution being development of the superconducting magnets that rely on cryogenics to function effectively. A comprehensive report on the economic impact of MRI scanners was produced in 2013[16] and an overview of MRI scanners and STFC's role is provided below.

MRI scanners

5.4. MRI is the result of over 70 years of research. High-resolution MRI scanners provide vital information on the human body that improves success rates of surgery and saves lives. **The global market for MRI systems is expected to reach £6.9 billion by 2018**[17]. An earlier report[18] established that **MRI manufacturing is worth up to £137 million to UK GDP and supports 2,200 jobs.**



Credit: © Tomas Hajek | Dreamstime.com

5.5. These impacts are supported by significant collaborations with the industry. For example, manufacturers involved include Siemens Magnet Technology, Philips Medical Systems, GE Healthcare and Toshiba Medical Systems. Furthermore, 16,400 MRI magnets worldwide are cooled by Air Products. Both, Air Products and Siemens Magnet Technology are members of the British Cryogenics Cluster (Figure 2.2 in section 2 of the report).

5.6. In addition to these impacts, there are significant impacts arising from MRI diagnostics capabilities

[16] The economic impact of physics research in the UK: Magnetic Resonance Imaging (MRI) Scanners.
[17] BCC Research.
[18] The economic impact of physics research in the UK: Magnetic Resonance Imaging (MRI) Scanners.

not included in these estimates. For example, MRI increases cancer detection rates, saves lives and reduces NHS costs with the following estimates highlighting some of the value of this activity:

- MRI is more than twice as effective as X-rays at detecting breast cancer in women classified at 'high genetic risk', particularly women carrying the BRCA1 gene mutation that is associated with a high risk of breast or ovarian cancer.
- MRI has improved the success rate of spinal surgery, saving the UK economy £166 million in lost output, absence management and healthcare costs.
- MRI supported diagnosis and treatment planning has reduced the numbers of limb amputations in primary bone cancer cases, leading to NHS cost savings of £5 million to £10 million each year.

5.7. STFC's role in MRI was in developing superconducting magnets, multifilament superconducting cables and superconducting joints in the 1970s and specific software for MRI in the 1980s[19]. These key developments of the early technology were transferred to Oxford Instruments, as described in paragraphs 5.12 – 5.19 below.

Other developments

5.8. Cryogenics is continuing to contribute to advances in medical care. For example, cryotherapy involves using extreme cold to freeze and destroy diseased tissue. Whilst it has long been used to treat skin conditions, advances in imaging allow cryotherapy to be carried out through keyhole surgery to treat tumours in the kidneys, bones (including the spine), lungs, and breasts. Advantages include reduced recovery times and hospital stays versus open surgery, reduced pain and physical scarring and reduced overall costs.

5.9. At MRC-Harwell's cryopreservation service, cryopreservation technology plays a key role in IVF[20] treatment, preservation of animal genetic resources, organ transplantation and other bio-medical applications.

5.10. Section 6 also presents an example of future technological exploitation with potential to impact upon health – this refers to Rapid Surface Chilling™ for the reduction of campylobacter contamination of poultry.

CHAMPIONING UK ENGINEERING CAPABILITIES

5.11. STFC funds and delivers world-class expertise across a wide range of engineering technologies, working closely with industry in consultative and collaborative capacities as illustrated by the following case studies:

5.12. **Oxford Instruments** is a leading UK technology company with a turnover in 2013/14 excess of £360 million[21]. It designs and manufactures high-technology tools and systems capable of fabricating, analysing and manipulating materials at the nanoscale. The company has worldwide sales to the science, energy, environmental, health and security industries.

5.13. Since the 1970s, STFC and Oxford Instruments have developed a mutually-beneficial relationship, building on scientific discoveries and their industrial application to create technological benefits for both organisations, including superconducting wire and magnets, particle accelerators and applications of cryogenic technology and creating impact for the UK's economy and society.

5.14. One of the most notable impacts from this relationship has come from the early development of superconducting wire. This has been applied to various fields of scientific research, most notably for medical use in MRI scanners. The collaboration between Oxford Instruments and STFC laid the foundations for the now worldwide MRI industry as described earlier in this section.

[19] http://www.stfc.ac.uk/resources/PDF/OEMRICaseStudy.pdf
[20] IVF (In vitro fertilisation). http://www.nhs.uk/Conditions/IVF/Pages/Introduction.aspx
[21] http://www.oxford-instruments.com/news/2014/june/announcement-of-preliminary-results-for-the-year

5.15. Early research has also contributed to ITER, a major international programme mentioned earlier in the report (paragraph 2.12). The process being used at ITER requires very strong magnetic fields, and Oxford Instruments won a major contract to supply superconducting strands to ITER. Although the structure of this strand has evolved considerably since the earliest multifilament wire designed at RAL (by Martin Wilson and colleagues), the design can still be seen as a long-term beneficiary of the innovations that have been generated through the collaboration between STFC and Oxford Instruments.

5.16. Quantifying and attributing the financial and wider benefits arising from this long-standing relationship is not straightforward given the number of transactions involved and the lack of comprehensive data to capture all relevant economic activities. Nevertheless, Oxford Instruments executives suggest that according to conservative estimates the company has gained a cumulative financial benefit in excess of £100 million from this longstanding relationship.

5.17. In terms of current collaborations with STFC, Oxford Instruments is a key supplier to STFC's ISIS neutron scattering facility and Diamond Light Source, providing superconducting magnets to extend the capabilities of these two major international facilities. The design and manufacture of these magnets has been carried out with considerable exchange of knowledge between the facilities and Oxford Instruments.

Oxford Instruments superconducting magnets. Credit: STFC

5.18. Building on the success of the sales to ISIS, Oxford Instruments has supplied similar equipment to comparable research institutions overseas, with benefits to Oxford Instruments' revenue stream and the UK's balance of trade. The liquid cryogens required by current superconducting magnets are becoming increasingly expensive, and Oxford Instruments has invested considerable resource in developing cryogen-free refrigeration. ISIS has collaborated with Oxford Instruments to design and test this dry cryostat technology. As a result Oxford Instruments released a product in 2013, called ISISStat®, which is being marketed for other neutron scattering experiments globally.

5.19. Collaborative, forward-looking programmes continue to involve both Oxford Instruments and STFC. For example, a joint project between Oxford Instruments, the Hitachi Laboratory at Cambridge, and STFC, is developing platform technology for quantum computing, which could revolutionise computer performance. It uses Oxford Instruments' world-leading, cryogen-free refrigerators, which can reach extremely low temperatures.

Shakespeare Engineering

5.20. Staff from STFC's Accelerator Science and Technology Centre at Daresbury Laboratory are working with[22] specialist UK company Shakespeare Engineering Ltd to help it access the market for superconducting radio frequency (SRF) cavities, used in particle accelerators around the world and reliant on cryogenics to function. Until now, no UK company has had the capability to compete in this market, with only a handful of suppliers from the US, rest of Europe and Asia competing in this market. Shakespeare Engineering, which has 150 staff, has historically specialised in Formula 1, oil and gas. The move into cryogenically-cooled SRF components has required close working with STFC's radio frequency and cryogenics group and investment in new staff and facilities.

[22] Through STFC's Innovation Partnership Scheme.

5.21. The market for such SRF cavities is anticipated to grow strongly over the next 10 years with possibly as many as 10,000 units required. Based on the company's own assessment, a single unit may sell for around £370,000, and the company is aiming to achieve 20% market share. If this materialises, sales over a 10-year period could be around 1 billion euros (£740 million) globally, bringing associated jobs and GVA in this sector to the UK for the first time.

EXPANDING FUTURE ENERGY SOURCES

5.22. Cryogenic liquids are widely used in a variety of industrial applications, but their application in the energy sector is only just emerging. A primary example of the role of cryogenics and STFC's support in this area is the Dearman engine, described below.

Dearman engine

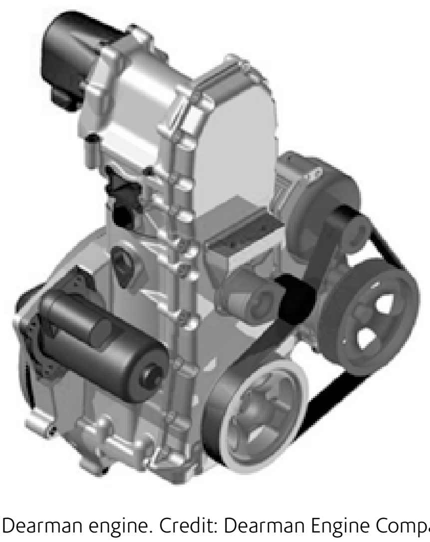
5.23. The Dearman engine[23] is a novel clean piston engine, powered by the expansion of liquid air or liquid nitrogen. The only exhaust is cold air (as opposed to noxious oxides, e.g carbon dioxide and carbon monoxide, and other pollutants). The engine could significantly reduce the emissions of refrigerated transport, buses and commercial vehicles, and help companies to make substantial fuel savings.

5.24. When air is cooled it becomes liquid at around -194C and is known as 'liquid air'. The liquid air in the Dearman engine expands, powering the engine, which emits clean, cold air. The engine also provides free cooling, and so is particularly useful for cold chain transport and bus air conditioning, which consume 20% of a vehicle's diesel fuel. Importantly, the engine is economical to build and maintain.

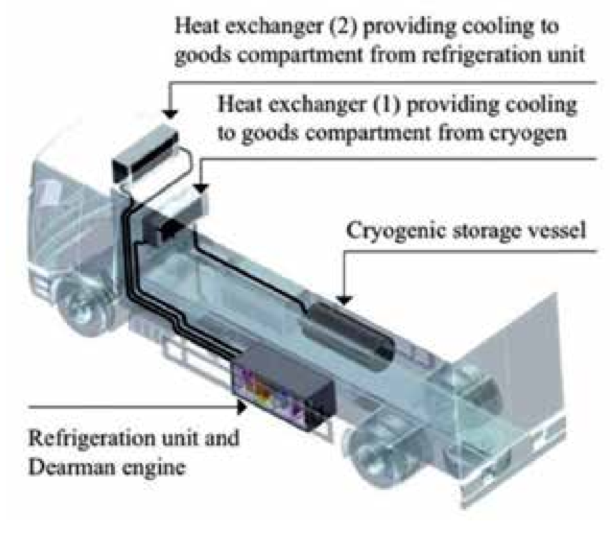
5.25. British inventor Peter Dearman created the Dearman engine in his garage in the 1990s. Dearman's new method involves mixing a heat exchange fluid with liquid nitrogen to improve the heat exchange and speed up the phase change from liquid to gas. This gives a faster and more complete expansion than would otherwise be obtained and leads to a more efficient engine.

5.26. Liquid air is not currently produced commercially in the UK, but excess liquid nitrogen is produced as a by-product of liquid oxygen production. While it is an energy-intensive process, there is spare capacity for liquid nitrogen production and substantial commercial interest. Liquid air also offers the possibility of using surplus electricity from renewable sources such as wind turbines – effectively storing the energy produced for when it is needed.

5.27. Dearman is initially concentrating on how this technology could replace diesel engines in commercial vehicles, starting with the secondary motor that drives refrigeration in food-delivery trucks. This has the potential to eliminate a significant, but often-overlooked source of carbon and nitrogen oxides emissions.



Dearman engine. Credit: Dearman Engine Company Limited



[23] http://www.dearmanengine.com

5.28. Modelling of potential uptake suggests the following benefits[24] :

- Refrigerated trailers with the Dearman engine could lead to cumulative net UK savings of **£76 million** by 2025 and **880,000** tonnes of carbon emissions[25] .
- A commercial vehicle fleet of 36,000 vehicles by 2025 could lead to annual net savings of £37m and 404,000 of carbon emissions.
- Use of liquid air as a fuel could lead to a new market for UK industrial gas producers of **10,000 tonnes** per day by 2025, worth some **£130 million** per year at 5p per kg with GVA of **£26 million**.

5.29. Dearman is a member of two consortia, which have jointly been awarded £3.6 million by the UK's innovation agency, Innovate UK:

i. a 2013 grant to build and test a liquid air engine fitted in a commercial vehicle delivering zero emission refrigeration; and,

ii. a second grant to demonstrate a heat hybrid system as the primary powertrain for buses and urban commercial vehicles[26].

5.30. A representative from STFC's cryogenics and magnetics team at RAL, with expertise in design and use of cryogenics within the engine, sits on the Dearman Board advising the partners involved in the development of the liquid air engine. Due to the commercially sensitive nature of this agreement, no further information can be disclosed at this stage. The engine is now in trials, initially to drive lorry refrigeration units and low-volume commercial production is forecast for 2016.

Alternative energy sources – Bioenergy

5.31. Cryogenics has played a significant role in the storage and transport of energy sources and in particular natural gases, enabling liquefaction of gases since 1964. The storage volume for the LNG is extremely small compared to the gaseous alternative. Surface transport of the energy source is therefore far more efficient since more volume can be transported in its liquid state. Cryogenic Liquid Fuels look like playing an increasing role in energy in the future too e.g. in relation to Liquefied BioGas (LBG), which is emerging as an alternative energy source in automotive, marine and even agricultural applications. Currently, a large number of projects worldwide, including in the UK, are researching optimal sources and methods to increase the produced volume of biogas/bioenergy to become an economically feasible solution. The UK has a binding target under the European Commission's Renewable Energy Directive to source 15% of its overall energy from renewable sources by 2020, with bioenergy having the potential to provide about 30% of the 2020 target through; biofuels, bio refineries, and the recovery of energy from the biomass portion of waste (including anaerobic digestion).

5.32. When processed to a higher purity standard, biogas is called Renewable Natural Gas (RNG) or Bio-methane and can be used as an alternative fuel for natural gas vehicles. For the same reasons as for natural gas, liquefying the biogas will bring volume and range advantages.

5.33. Bennamann Ltd is a high-tech start-up that has been investigating a solution to enable the generation and storage of bio-methane for distributed domestic power generation and heating, and became an alumni of the ESA Business Innovation Centre[27] (BIC) at Harwell in early 2013. Whilst based at the ESA BIC, the company worked with the STFC's cryogenics and magnetics team who assisted with the design of an efficient cryogenic bio-methane storage system based around the Bennamann Process™ and a micro-anaerobic digester[28] according to the Bennamann Cycle™[29] that has the potential to achieve a zero carbon footprint. Both of these systems have been

[24] Centre for Low Carbon Futures (2014) Liquid Air on the Highway.
[25] Greenhouse gas emissions caused by energy use are measured in units of kg, or tonnes of, carbon dioxide equivalent (tCO2e).
[26] As part of its energy storage programme the Centre for Low Carbon Futures has supported the creation of a new centre for cryogenic energy storage at the University of Birmingham in partnership with the University of Hull - the Birmingham Centre for Cryogenic Energy Storage (BCCES). The EPSRC is providing £6m to the project, with additional £6m of contributions from industry and University. BCCES is closely working with the industry including with the Dearman Engine Company.
[27] The ESA Business Incubation Centre (BIC) Harwell is part of a Europe-wide network providing support for start-ups and research teams commercialise technologies designed to advance space exploration into products and services for non-space markets.
[28] Anaerobic digestion consists of processes that enable microorganisms to break down into biodegradeable material in the absence of oxygen. In this case, the term refers to converting the organic waste and residues into biogas that can be used to produce heat, electricity or vehicle fuel.
[29] Patents were pending for both the Bennamann ProcessTM and Bennamann CycleTM at the time of completion of this study.

installed into a mobile test platform that can be integrated and controlled via a web-based application. Bennamann is currently using this to investigate anaerobic digestion of garden waste from large country estates and parks as an alternative energy source for these large properties (which the UK account for around 10% of the national housing but surprisingly 45% of electricity and heat usage[30]).

5.34. This liquid gas can also be used in the production of electricity and heat, converting existing cars into methane-powered vehicles and the end product can be used as fertiliser. Bennamann also envisage farmers using this cycle in their crop rotation, potentially providing a new income stream for their farm.

MAKING SPACE MISSIONS POSSIBLE

5.35. The space industry is a major UK success story, growing from 68,000 jobs and £5.6 billion GVA in 2006/07[31], to 106,000 jobs and £10.8 billion GVA in 2014[32], equivalent to 8.5% annual growth. Around 71% of the sector consists of small and medium-sized firms. The UK Government is committed to further grow the sector. *The Space Innovation and Growth Strategy 2014-2030*[33], published in 2010 set a key target to grow the UK's share of the world's space economy from 6.5% to 10% by 2030. By today's estimates this would lead to a UK sector with £40 billion per annum of space-enabled turnover. The *Space Innovation and Growth Strategy* also set an interim target of 8% of the world's space economy by 2020, in order to secure a space-enabled turnover of £19 billion in today's terms.

5.36. STFC plays a key role in achieving this, through its astronomy and space science programme. The programme provides funding to universities and research institutions in order to investigate some of the highest priority questions in astrophysics, cosmology and solar system science, and supports technical activities at STFC's UK ATC and RAL Space. Support specifically for space science is delivered through the UK Space Agency for project build activities, and through STFC research grants for mission science exploitation. Much of the work of RAL Space is in collaboration with UK university research groups and a range of institutes around the world. Most of these collaborations have been set up to support the European Space Agency (ESA) and NASA missions, although RAL is also working on projects with other countries and organisations including Australia, Japan, Morocco, Pakistan, Russia and the European Union.

5.37. Cryogenics is vital in making space exploration successful. Not every space instrument requires cryogenic-cooling. However, cryocooling of vital systems such as detectors, optics, and the body of space satellites is crucial, to reduce, for example, the signal-to-noise ratio of satellite instruments and telescopes and capture clear pictures given the distances involved. Furthermore, other space-related technologies including rocket propulsion require cryogenics.

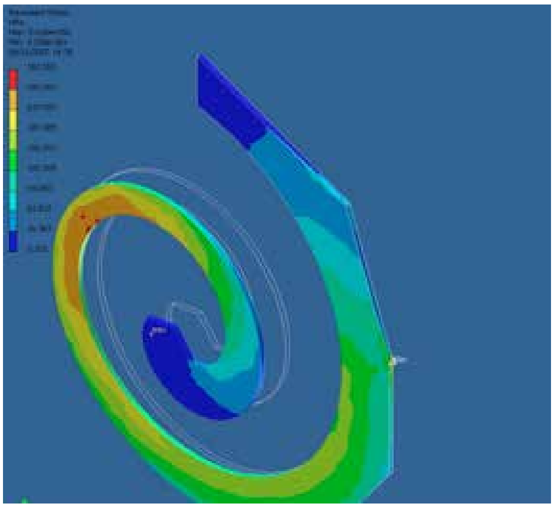
5.38. A selection of space-enabling technologies involving cryogenics and their applications that are supported by STFC are set out below.

5.39. Crycoolers for space Applications: Cryocoolers are a key enabling technology for space-based science and astronomy and STFC's RAL has been a world-leader in this technology since the 1980s, having successfully developed cryocooler designs that have been flown on many ESA missions, such as the Planck Explorer mission described below.

[30] http://www.bennamann.com/technology/
[31] Oxford Economics (2009) The Case for Space: The impact of space derived services and data.
[32] UK Space Agency (2014) The Size & Health of the UK Space Industry 2014.
[33] http://www.ukspace.org/wp-content/uploads/2013/11/Space-IGS-Space-Growth-Action-Plan-2014-2030-Nov-2013.pdf

5.40. Reliability is absolutely critical for these applications, as the coolers have to be able to survive in space for the length of the mission. One of the core technologies of the compact space cooler is the long-life diaphragm spring technology that has been jointly developed by the University of Oxford and RAL[34].

5.41.



Finite Element (FE) model of spring design. Credit: STFC

The team at RAL have continued development of these coolers to respond to the increasing complexity of satellites, with the 20K then 10K two-stage Stirling Cooler, followed by the 4K Stirling + Joule Thomson cooler, and now with the 2K cooler, which is under current development. These compact space coolers have been re-engineered for improved scale, size, precision, durability and cost, with the UK competing internationally with France, Holland and the United States.

5.42. Driven initially by the needs of applications in space, parts of the technology are patented, and licences have been granted for manufacture of space coolers in Europe and America. The RAL cooler design was licensed to Ball Aerospace and British Aerospace, Matra Marconi and EADS Astrium – the latter having produced and sold a large number of coolers[35].

5.43. Continuous improvement of the technology has also been achieved through other collaborations as described by Dr. Martin Crook from the cryogenics and magnetics team at RAL[36]: *"For some years we have been aware of the potential for rare-earth coatings to enhance the performance of our coolers but despite numerous attempts were not able to implement a flight-worthy solution. However, thanks to the development work carried out by Professor Ehiasarian at Sheffield Hallam University, an excellent coating was realised that is suitable for a flight qualification programme. Directly through that work, our 10-15K Stirling cycle cryocooler has demonstrated a clear advantage over other technologies at this temperature, and is the baseline choice for scientists currently entering instrument proposals for forthcoming missions such as EChO, a space-based observatory to characterise the physics and chemistry of exoplanet atmospheres."*

5.44. As mentioned in paragraph 5.34, teams at STFC's RAL (including the cryogenics and magnetics team) contribute to **ESA's Planck explorer mission.** Planck is ESA's mission to observe the first light in the Universe with the aim of answering questions about how galaxies, stars, planets and the Universe were formed[37]. It was launched in May 2009, and was expected to complete two whole surveys of the sky. In the end, Planck worked perfectly for 30 months, about twice the lifespan originally required, allowing completion of five full-sky surveys[38]. STFC provided a sophisticated thermal analysis for the design of the system, as well as developing the extremely complex 4 Kelvin long-life cryocooler for the mission. Furthermore, STFC provides on-going funding for five post-doctoral researchers on the Planck project.

[34]In 1978, the Department of Engineering Science at the University of Oxford was awarded a contract to construct a small, long-life Stirling cycle cryocooler for cooling an infrared instrument called ISAMS (Improved Stratospheric and Mesospheric Sounder), aboard the UARS (Upper Atmosphere Research) platform. These coolers were jointly developed by groups in the Physics and Engineering Departments at Oxford and at RAL. The two devices were designed to provide 1 W of total focal plane and detector cooling. The instrument was launched in September 1991 aboard the Space Shuttle and operated for 180 days before the instrument failed due to a chopper problem.

[35]The original licensing agency was the National Research and Development Corporation, British Technology Group – from a presentation by Tom Bradshaw (17 May 2011, Daresbury) - http://www.esa-bic.org.uk/resources/pdf/2011-05-17compactspacecoolers.pdf

[36]http://rseeccleston.blogspot.co.uk/2013/01/meri-pvd-coatings-heading-for-space.html

[37]Planck, originally named COBRAS/SAMBA, was renamed on approval of the mission in 1996 in honour of the German scientist Max Planck (1858-1947) who won the Nobel Prize for Physics in 1918.

[38]Preliminary results of observations made by the Planck space telescope released at the end of 2014 provide the most precise confirmation so far of the Standard Model of cosmology, and also place new constraints on the properties of potential dark-matter candidates (http://sci.esa.int/planck/55059-conference-announcement-planck-2014/)

5.45. Industry from all over Europe and the United States contributed to the development of Planck. ESA's prime industrial contractor for Planck was Thales Alenia Space (France), and the following UK-based companies have been involved in building the Planck spacecraft[39]:

5.46. Other space applications involving cryogenics technology developed with contributions from STFC-supported teams include:

- **The Herschel Space Observatory (Herschel):** Operating until April 2013, this was considered the largest astronomical telescope ever put into space and took extensive images of the sky that are still being analysed. The Herschel-SPIRE (Spectral and Photometric Imaging Receiver) instrument was one of three instruments on board. It was built by an international consortium of more than 18 institutes, with RAL Space overseeing the thermal design, build and test of SPIRE. Over 500 peer-reviewed publications to date have used SPIRE data and the benefits of this research are expected to continue for years to come.

- **The James Webb Space Telescope (JWST):** This is the successor to the Hubble Space Telescope and is a global collaboration due to launch a new space observatory in 2018. On board there will be four instruments, one of which, MIRI (Mid-Infrared Instrument), was developed by a consortium of 27 institutions from 10 countries led by STFC's UK ATC in partnership with NASA's Jet Propulsion Laboratory. Cryogenic-cooling minimises background thermal radiation that would otherwise swamp the signal being detected. The coolers on MIRI are based on UK technology and produced in the United States. The total cost of MIRI is £150 million; the UK budget for the project is £19.8 million plus a further £3.4 million for testing with 65 scientists involved, plus industry partners. **The overall UK investment (£23.2 million) to date is expected to lead to GVA of £24 million and 264 jobs in the UK**[40] .

5.47. Finally, it is worth noting that STFC has been involved in successive developments in technology leading to the miniaturisation of cryocoolers, producing a small-scale cooler that is also revolutionary in the terrestrial market. It offers the reliability and longevity of space-based mechanisms with a predicted performance that comfortably exceeds the market benchmark cooler in its class. Key potential applications[41] include:

- germanium-based detectors
- infrared detection and imaging markets
- military applications, e.g night vision goggles and vehicle tracking, and
- imaging, e.g thermal imaging of buildings for heat loss.

Companies contributing to the development of Planck	Planck spacecraft equipment provided
AEA Technology (now Ricardo AEA)	Batteries
Analyticon	Attitude Control Management System – Simulations
BOC Edwards (the Edwards group was sold to Sweden's Atlas Copco in 2013 – BOC is a member of the British Cryogenics Cluster)	Refurbishment of Cryogenic Vacuum Support Equipment – Manufacturing
Datasat	Electrical Engineering Support
MT Satellite Products	Reaction Control System - Hydrazine Tanks
System International	Service Module Engineering Support

[39] http://sci.esa.int/planck/34787-industrial-team/
[40] These calculations are based on direct, indirect and induced effects using the multipliers from the UK Space Sector Report (https://www.gov.uk/.../uk-space-industry-size-and-health-report-2014). GVA for the sector is estimated at £145,000 per employee and the economic multiplier is 2.2.
[41] http://www.esa-bic.org.uk/resources/PDF/SmallScaleCryo-Coolers.pdf, SpaceTech, 2014.

MONITORING AND UNDERSTANDING OF ENVIRONMENTAL AND CLIMATE CHANGES

5.48. Cryogenics also plays an important role in better understanding environmental and weather-related issues, including contributing to achieving improved weather forecasting through satellite data, which has been valued at £400 million-£1 billion per year[42]. The following projects illustrate the importance of cryogenics in this area and the contribution made by STFC teams and their role, in collaboration with other scientists and industry.

5.49. Since 1991, **Along Track Scanning Radiometers** (ATSR) have been flown on three of ESA's earth observation missions. Designed primarily to measure sea surface temperatures, the ATSR series[43] has produced a 17-year data set. This data archive for users is hosted at RAL on behalf of NERC's[44] Earth Observation Data Centre. ESA's ENVISAT satellite successfully launched in 2002, carried the Advanced Along Track Scanning Radiometer instrument (AATSR).

5.50. The AATSR was the third in series of UK-instruments, developed by a consortium comprising NERC, STFC, Astrium UK, and other industrial partners, also benefiting from a significant contribution from Australia[45]. RAL Space provided subsystems and laboratory calibration and the reference data processing system for AATSR. In addition, they provided the low vibration cooler electronics for MIPAS[46], an infrared spectrometer that measured pressure, temperature and trace gases. The in-flight performance of the AATSR instrument is continuously monitored at RAL, and the Met Office monitors AATSR data in real time.

SLSTR Calibration Facility at STFC RAL Space

5.51. The fourth ATSR, called the **Sea and Land Surface Temperature Radiometer** (SLSTR) is being developed by RAL Space scientists and engineers, with Thales playing a key role in the instrument design. This marks an important element of Europe's future operational infrastructure for environmental observations, and will capture highly accurate sea surface temperature measurements until post 2025. This is the first in a whole series of Copernicus[47] and Met Office sensors to be calibrated at RAL. In addition, significant new technology was developed to enable the programme, much of which has been successfully spun out to commercial products. For example, the design concept for SLSTR is currently being developed for flight by the instrument prime contractor Selex Galileo[48].

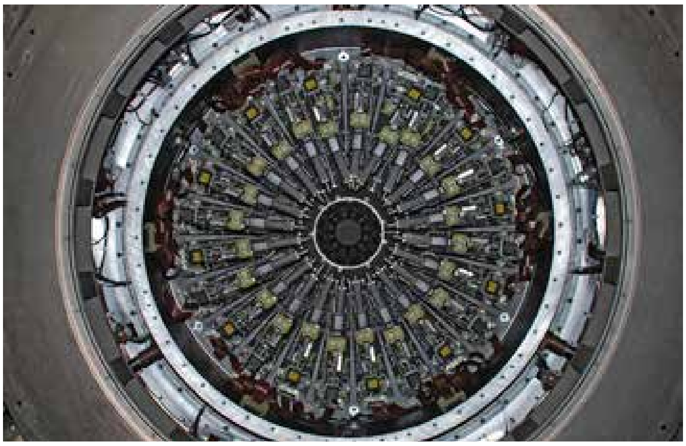
[42]Oxford Economics 2009 The Case for Space: The impact of space derived services and data.
[43]ATSR-1 was initially funded by the (then) Science and Engineering Research Council (SERC) a predecessor of STFC, and following a reorganisation of UK research organisations, by the Natural Environment Research Council (NERC), who continued and enhanced the programme with ATSR-2. The first two instruments were designed by the Rutherford Appleton Laboratory (RAL) as experimental scientific instruments. The current AATSR programme, has seen the ATSR series progress to operational status. The first three ATSR instruments were also supported by the (then) Australian Space Office and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The fourth sensor, currently designated SLSTR, has full operational status within the EU's Global Monitoring for Environment and Security (GMES) programme (http://atsrsensors.org/aboutATSR.htm).
[44]The Natural Environment Research Council (NERC) is the UK's largest funder of independent environmental science, training and innovation, delivered through universities and research centres.
[45]http://www.leos.le.ac.uk/aatsr/Image%20Gallery/index.html
[46]ttps://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/mipas.
[47]www.copernicus.eu.
[48]SELEX Galileo Inc. is a US subsidiary of Selex ES, a leader in defense electronics, aerospace, data, infrastructure, land security and a member of the Finmeccanica group of companies - Italy's main industrial group, leader in the high technology sector, and ranks among the top ten defence groups worldwide (http://www.selexgalileo.com/about-us and http://www.finmeccanica.com).

5.52. UK ATC, along with the Universities of Leicester and Edinburgh, has also designed and developed a short-wave infrared spectrometer, GHOST (Green House Observations of the Stratosphere and Troposphere). This is a world-first NERC/STFC-funded project to build an instrument for environmental modelling. The GHOST spectrograph is housed within a cryostat module, built for UK ATC by AS Scientific. The cryostat maintains a detector temperature of 80K, and reduces thermal background radiation. Keeping the entire optical module at cryogenic temperatures also ensures environmental and dimensional stability. GHOST will provide fine-scale greenhouse gas measurements and improve our understanding of the Earth's natural carbon cycle. In particular it will give NASA's 2015 Global Hawk mission improved capabilities to measure greenhouse gases and this new knowledge could inform future global policy on climate change. According to Professor Gillian Wright, Director of UK ATC: *"The shipping of GHOST to NASA is an important milestone in transferring technology developed for astronomy to innovative instruments for Earth observations. It will offer the UK additional capabilities to deploy GHOST or similar instruments on our own national airborne research platforms."*

LEADING IN GROUND–BASED ASTRONOMY

5.53. STFC is a world-leader in astronomy and plays a key role in providing ground-based cryogenic instrumentation for new astronomical telescopes and instruments for the world's great observatories. Examples of key projects[49] in this area of work include:

- The Atacama Large Millimetre Array (ALMA): ALMA is a global partnership to develop the largest telescope ever constructed to operate at the very highest radio frequencies and study star formation across cosmic time. The UK is a major partner in ALMA, which will allow astronomers to observe cold regions of the Universe with unprecedented clarity. In November 2014[50] a ground-breaking image of a protoplanetary disc, a dense rotating gas around young star, was revealed by ALMA. These new ALMA images reveal observations never seen before and represent an enormous step forward in the understanding of how planets form. The total cost of ALMA is £0.9 billion, with a UK component of £52.5 million. Cryostats were made at RAL for the 66 antennae and are located 5,000 metres above sea level in the Atacama Desert, Chile. Each cryostat houses 10 receivers mounted on quick



KMOS 24 arms. Credit: STFC

Protoplanetary disc around HL Tauri. Credit: ESO

[49] http://www.stfc.ac.uk/2718.aspx

release cartridges cooled to 4 Kelvin (-269 Celsius). The UK has undertaken several critical parts of the system design and UK scientists expect to be at the forefront of the scientific discoveries made by ALMA. The cost of cryogenics team inputs is estimated at over £16 million, suggesting generation of £16.5 million GVA and approximately 182 jobs[51].

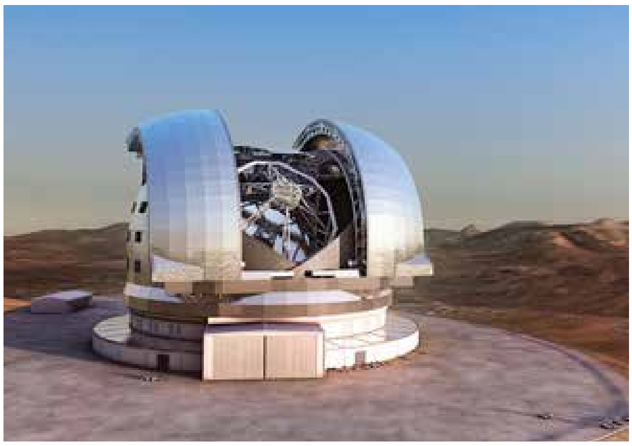
- **The Very Large Telescope** (VLT): The VLT is the world's most advanced optical instrument, operated by the European Southern Observatory (ESO) in Chile. The K-band Multi-Object Spectrograph (KMOS) is a second generation instrument designed for operation on the VLT. This is a cryogenically-cooled instrument developed by STFC in partnership with Durham, Oxford and Bristol universities and colleagues from the Max-Planck Institut and Munich University) for installation on the VLT. STFC's UK ATC was responsible for construction of the cryostat, the robotic pick-off arms, the cable co-rotator and the final assembly and test of the instrument. KMOS has brought new capabilities for observing 24 galaxies simultaneously, allowing astronomers to build galaxy samples of unprecedented size and quality. Of the £6 million capital budget for KMOS, £4.3 million was spent within the UK either in academic institutes (60%) or industry (40%). **Cryogenics accounted for 30% of UK spend in this project suggesting GVA of £1.3 million and 15 jobs in the UK**[53].

5.54. Other future projects in this area include:

- **The MOONS project:** MOONS is a £18.5 million international project to develop Multi-Object Optical and Near-infrared Spectrographs (MOONS) for the VLT. The project aims to create a 3D map of the galaxy allowing astronomers to see obscured areas in the Milky Way. STFC is leading a £7.8 million contract that includes developing the cryostat system needed to cool MOONS down to -170°C, vital to enabling the infrared observations needed to penetrate galactic and intergalactic dust clouds. MOONS is scheduled to be operational by 2019. **This STFC investment is expected to lead to GVA of £2.6 million and 30 jobs in the UK.**

- **European Extremely Large Telescope (E-ELT):** The E-ELT will be the largest infrared telescope in the world at 40m aperture and is scheduled for completion at the European Space Organisation (ESO) by 2022. It will help answer some key questions in astronomy, including the first objects in the Universe and super-massive black holes. Both the UK Programme Director and the UK Project Office are based at UK ATC and over 100 UK scientists are involved. UK industrial contracts of £80 million are anticipated over the next decade with cryogenics playing a key role.

- **Square Kilometre Array (SKA):** The SKA will be the global radio astronomy observatory for at least the first half of this century. One of the most complex scientific instruments ever built, it will consist of an array of around 4,000 dishes, with associated infrastructure, capable of all-sky imaging. Cryogenic-cooling will be an integral component of the SKA. STFC is part of an international consortium developing the UK technical programme led by the universities of Cambridge, Manchester and Oxford, together with UK industry. The project cost of around £1.2 billion, includes a UK contribution of 15% of the construction cost of phase 1. Oxford Cryosystems, a UK company, is providing custom-



Artist's impressions of the E-ELT. Credit: ESO

[50]Source: ALMA (ESO/NAOJ/NRAO)
[51]These calculations are based on direct, indirect and induced effects using the multipliers from the UK Space Sector Report (https://www.gov.uk/.../uk-space-industry-size-and-health-report-2014). GVA for the sector is estimated at £145,000 per employee and the economic multiplier is 2.2.
[52]http://www.stfc.ac.uk/ukatc/35339.aspx
[53] https://www.dur.ac.uk/cfai/projects/kmos/

built cryocoolers[54] for the radio receivers in the first phase, with potential for further contracts to support 1,000 in phase 1 and up to 12,000 cryocoolers in phase 2 of the entire project.

ACCELERATING GLOBAL SCIENTIFIC DEVELOPMENTS AND EXPLOITATION

5.55. Cryogenics is a fundamental technology for a wide range of scientific experiments including the functioning of particle accelerators and lasers as described below. It is not always possible to quantify the scale of these impacts due to methodological issues relating to assessing impact of science in development and enabling technologies (as described in section 4 of the report). Nevertheless, the examples presented in this section highlight that STFC's cryogenics expertise and continuous support in this area of work contribute to building the UK's international reputation in scientific and technological excellence and UK companies' competitive position in the global market.

Accelerators

5.56. Measuring the way a beam of particles is scattered when it passes through a material can be used to investigate atomic-scale structure and dynamics. This improves understanding of existing materials and development of new materials, thus supporting new discoveries and technologies. For example, new energy sources, cancer treatments and medical discoveries have all involved particle accelerators. Since the 1930s, scientists have developed particle accelerators to enable these studies. These are large and expensive facilities where beams of particles are accelerated at speed and diverted into beamlines for individual experiments to be undertaken. Cryogenics has now become a key technology for particle accelerators and colliders, mostly associated with superconductivity.

5.57. An estimated 30,000 particle accelerators are in use throughout the world. According to one US report, the products processed, treated or inspected by particle beams have a collective annual value of more than £312 billion[55]. The current market for medical and industrial accelerators is more than £2.2 billion a year, with estimated annual future growth of 10%[56].

5.58. The UK is playing an internationally-leading role in accelerator technology. STFC operates or hosts the UK's large particle accelerator facilities (ISIS and Diamond Light Source), funds UK access to international research facilities (including CERN, ILL and ESRF), and helps develop the accelerators of the future, such as the European Spallation Source (ESS). By operating these facilities, knowledge emerges from which we understand fascinating new science, or gain an understanding of current problems in industry. An overview of these facilities is provided below.

5.59. **ISIS** is an STFC world-leading centre for research in physical and life sciences that produces beams of neutrons and muons that allow scientists to study materials at the atomic level using a suite of instruments, often described as 'super-microscopes'. ISIS is recognised as a large-scale facility that has a culture of innovation, providing both scientific excellence and leadership. Over 3,000 scientists are supported internationally with research spanning advanced materials, clean energy, pharmaceuticals and health.

5.60. Most ISIS beamlines use cryogenic and high magnetic fields, and the sample environment is based on cryostats and superconducting magnets. Conventionally the sample environment is provided by liquid helium and liquid nitrogen bath cryostats. By cooling a sample, energy is extracted from it, and this lower energy state leads to less molecular vibration, and the ability to view the physical properties of the material more clearly. As described in paragraph 5.14, ISIS in collaboration with Oxford Instruments have developed a new cryogen-free system called ISISStat®. In addition, collaborations led to the development of advanced superconducting magnets, achieving increased sales of leading-edge products for Oxford Instruments in Europe and further afield.

[54] http://www.catapult-ventures.com/news/oxford-cryosystems-helps-push-the-boundaries-of-the-known-universe
[55] http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf
[56] Accelerators for America's Future 2010.

5.61. ISIS also builds on 30 years of international collaboration as demonstrated by the European Spallation Source (ESS) and the Muon Ionisation Cooling Experiment (MICE):

- MICE is an international experiment located at STFC's Harwell Oxford Campus to assess the effect of cryogenic-cooling on a high power muon beam. Construction of this experiment started in 2005 and has been divided into a number of stages. The fourth stage, completed in 2014, provided the MICE Muon Beam on ISIS with state-of-the-art beam-line instrumentation and world-leading cryogenic technology. Muon accelerators have the potential to deliver uniquely sensitive measurements of the properties of neutrinos thereby providing new and fundamental insights into the nature of matter. The UK project costs are £41 million to Stage IV with a further US cost of $26 million. The location of the project at the ISIS facility at RAL demonstrates the UK's leadership in accelerators and cryogenic-cooling.
- The ESS[57], due to start operation in 2019, will be the most powerful particle accelerator yet. In 2013, ISIS signed a Memorandum of Understanding with ESS on an extensive programme of technical collaboration, including accelerator diagnostics and advice on the cryogenic sample environment, thereby supporting its successful development and enabling the discoveries of the future.

5.62. **Diamond Light Source**, the UK's national synchrotron science facility, speeds up electrons to near light speeds so that they give off a light 10 billion times brighter than the sun. Diamond's radio frequency cavities are superconducting and are used to accelerate the electron beam as they circulate and release energy in the direction of laboratories known as beamlines. Over 3,000 visiting scientists each year, from both academia and industry, use these beamlines to study a vast range of subject matter, from new medicines and treatments for disease, to innovative engineering and cutting-edge technology. One recent example being the usage of the facility to develop a new vaccine for foot-and-mouth disease. Notable beamlines include I10, I12 and I15.

5.63. In relation to new developments, Diamond chose UK ATC to design and construct a vacuum operating six-axis Goniometer, which is an instrument that rotates an object to a precise angular position. This represents a novel approach as traditionally, the goniometers have not had to operate in a vacuum or provide cryogenic-cooling of the samples under study. The combination of cooling, vacuum and precision provided by Diamond's Goniometer will be unique worldwide. This novel instrument will explore protein and DNA samples in a range that is not currently accessible. Synchrotron X-rays will continue to contribute to structural biology's ability to explain things in detail, aiding drug design and important advances in understanding viruses and diseases.

5.64. ATLAS is one of the four main experiments at the Large Hadron Collider (LHC) at CERN[58]. It is designed to investigate the origins of the Universe and unravel some of the secrets of dark matter. The LHC has the largest cryogenic system in the world and is one of the coldest places on Earth. STFC's cryogenics and magnetics team at RAL had the overall design responsibility for the 25m diameter ATLAS magnets.

UK ATC Goniometer. Credit: STFC

[57] The European Spallation Source (ESS) is a multi-disciplinary research centre based on the world's most powerful neutron source to be based in Lund, Sweden. The first neutrons are expected by 2019 and the first experiments are planned to begin in 2023. http://europeanspallationsource.se/european-spallation-source

[58] European Organisation for Nuclear Research (Conseil Européen pour la Recherche Nucleaire).

5.65. Looking to the future, a major upgrade to the LHC will be required around 2020 to maintain scientific progress. Known as 'HiLumi-LHC', the project will increase the machines rate of collisions by a factor of 10 beyond the original design specification. The HiLumi-LHC design studies are due for completion at the end of 2015, at an estimated cost of £15.2 million[59] (£3.62 million of which represent EU's financial contribution), this excludes £4.35 million contribution by the United States. The ASTeC team at STFC's Daresbury Laboratory has been chosen to lead on the design study for a prototype of the cryomodule towards the Super Proton Synchrotron beams tests. The contract for the HL-LHC cryomodule is £362,300 and is based on collaboration between STFC, Lancaster University and CERN.

5.66. Furthermore, STFC helps UK companies take advantage of on-going opportunities to supply products and services to national and international facilities, such as CERN. STFC offers advice on the procurement opportunities available, and on how to access contracts at these facilities, as well as introducing companies to the UK liaisons for industry. Some of the cryogenic-related contracts that UK companies have with CERN include:

- AS Scientific, a UK company and global supplier of low-temperature engineering equipment won several contracts from CERN that led to an invitation to join a large consortium for work at ITER[60] on a €53 million project, with an expected share of £2 million-£3 million.
- Temati, a UK SME has been supplying CERN for ten years with highly sensitive carbon ceramic cryogenic temperature sensors for a number of different experiments. Temati's sensor is small, accurate, robust and stable. It enables CERN to detect temperature changes within five milliseconds, with greater speed than other sensors. As stated by Temati's Director, Paul Ryan, *"Our relationship with CERN has definitely helped us gain orders with new companies."*
- Wessington Cryogenics, a UK company supplies specialist gas storage tanks to customers including CERN. It has 120 staff based in the North East and has expanded during the economic downturn, due to its technological expertise being in demand.

5.67. Many UK companies state that the impact of winning contracts from international facilities is often greater than anticipated, as it boosts a company's reputation, enables development of new products and allows business to be won elsewhere, leading to a bigger return on investment.

New generation of particle accelerators

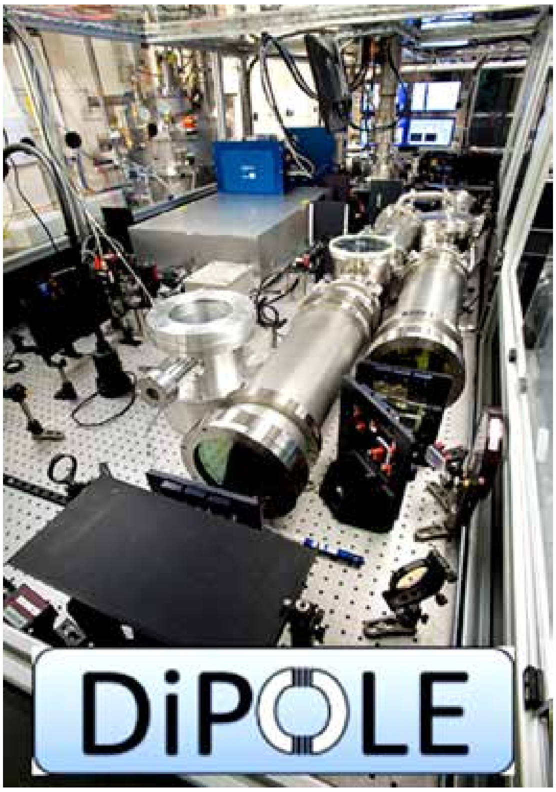
5.68. STFC is constantly exploring how accelerators could be made more powerful, or sophisticated, whether aiming to enhance existing machines with brand new techniques or to develop completely new accelerators. From the most fundamental research to the development of new products and technologies, such research is the key to unleashing new possibilities in experimentation thus speeding up the pace of scientific progress, and representing an invaluable asset for the UK. For example, at STFC's Daresbury Laboratory, there is the development of three cutting-edge accelerator systems. These are VELA (Versatile Electron Linear Accelerator) and ALICE (Accelerators and Lasers In Combined Experiments) – at the heart of which are four SRF cavities operating at 2 Kelvin cooled by the largest cryogenic plant in the UK, and EMMA (The Electron Machine of Many Applications), a proof-of-concept accelerator that could catalyse the development of a new generation of accelerators that contribute to new cancer therapies. Finally, CLARA (Compact Linear Accelerator for Research and Applications) is a proposed novel Free-Electron Laser (FEL) test facility to develop a next-generation light source.

High Power Lasers

5.69. STFC's Central Laser Facility (CLF) at RAL is one of the world's leading laser facilities, providing scientists from the UK and Europe with an unparalleled

[59] £1=1.38Euros on 1 March 2014.
[60] International Thermonuclear Experimental Reactor - an international project to design and build an experimental fusion reactor.

range of state-of-the-art laser technology. New advanced technology harnessed by CLF has led to the development of high-energy lasers known as DiPOLE (Diode Pumped Optical Laser for Experiments). DiPOLE lasers enable the timing of laser light pulses to be precisely controlled, by combining high pulse energy with rapid repetition rates. In developing DiPOLE, several technological challenges have been overcome, such as effective cryogenic-cooling of the laser amplifier, which improves thermal conductivity and provides optimal performance[61].



Dipole Laser. Credit: STFC

5.70. STFC has been working on developing a business case for commercialisation of the new laser. This is in response to one-third of the new academic and scientific facilities worldwide indicating a desire to upgrade to a higher specification system in the future. DiPOLE lasers would offer advantages, such as higher throughput for the £150 million laser peening (surface enhancement process) market[62]. DiPOLE will also enable compact, mobile sources for imaging and non-destructive testing for industries spanning aerospace, automotive, medical and nuclear. **It is expected that DiPOLE could be commercialised within the next five years.**

5.71. In the meantime, the value of recent contracts won by STFC in relation to projects integrating technology from the DiPOLE laser is around £18 million and includes:

- A leading-edge laser built by CLF and the University of Oxford for the billion-Euro XFEL facility that reveals matter's deepest secrets using X-ray flashes a billion times brighter than normal X-rays. Its £8 million, 30-month development being funded jointly by STFC and EPSRC will be a key part of the XFEL facility.

- This follows a £10 million contract won by CLF to develop new laser technologies for the HiLASE project in the Czech Republic.

[61]The second challenge relates to finding a suitable gain medium (the source of optical gain in a laser), transparent ceramic was selected and the third to finding laser diodes at reasonable cost.
[62]Laser peening is an innovative surface enhancement process, used for example to increase the resistance of aircraft fan blades to foreign object damage. According to industry estimates, the potential savings from laser peening are estimated to approach $1 billion when calculating this impact over all engines in the US Air Force fleet (LSP Technologies – a USA-based company, specialising in the application of high power lasers to improve the endurance, performance, and safety of manufactured components - http://www.lsptechnologies.com)

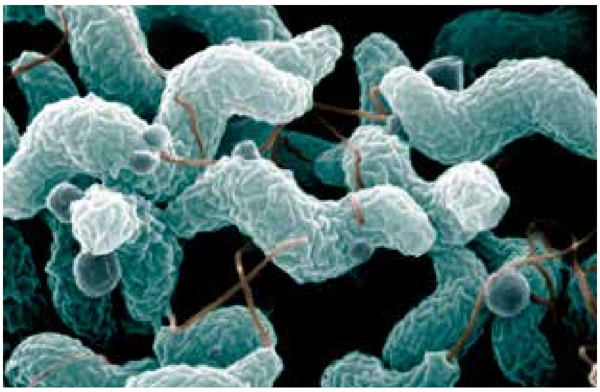
6. Future Potential for Technological Exploitation

6.1. This section presents examples of research and technological exploitation involving cryogenics that could potentially benefit the UK economy and society. STFC scientists follow these developments closely in order to identify future potential for scientific and technological exploitation that would capitalise on the UK's leading expertise in relevant fields including physics, superconductivity and cryogenics, and engineering. These developments are also of significant importance for potential applications in key sectors of the UK economy including defence and security.

Rapid Surface Chilling™ for the reduction of campylobacter contamination of poultry

6.2. Campylobacter bacteria have been implicated in human disease and they are the major cause of food poisoning in the UK and many other developed countries. The Food Standards Agency (FSA) estimate there are more than 280,000 annual cases of campylobacter poisoning with 100 deaths and a cost to the UK economy of £900 million. Most cases of campylobacter food poisoning originate from contaminated chicken and other poultry that has not been cooked or handled properly. A joint working group on campylobacter set up by Government[63] has set targets for reduction of birds carrying the highest level of contamination from 27% of the total population to 10% by 2015. FSA survey data for 2014 suggests that no retailers are achieving the end-of-production target for reducing campylobacter despite a number of initiatives. As a result, there remains an urgent need for new, effective approaches.

6.3. Perhaps the most promising line of research involves 'Rapid Surface Chilling™', a new cryogenic approach developed by BOC and Bernard Matthews Ltd. During recent industrial trials verified by FSA, **the surfaces of over 6,000 birds were rapidly chilled using a cryogenic vapour and this resulted in a reduction in campylobacter counts of 90 – 95%**[64]. Similar results were obtained in the United States where the US Department of Agriculture reported significant reduction in campylobacter contamination following 'flash freezing' of ground turkey using liquid nitrogen vapour.[65] BOC and partners are now developing a full-scale, commercial Rapid Surface Chilling ™ tunnel that will process poultry at a commercial line speed of up to 12,000 birds per hour. Jeremy Hall, Technical Director of Bernard Matthews Ltd, commented: *"This is a key milestone in the development of a solution to an enormous and serious health concern in the broiler industry. These latest results are good news for the UK consumer and endorse the considerable efforts we are putting in to help reduce Campylobacter at the poultry processing stage."*[66]



Credit: De Wood, Pooley, USDA, ARS, EMU.

[63] https://www.food.gov.uk/science/microbiology/campylobacterevidenceprogramme
[64] http://www.boconline.co.uk/en/processes/food-freezing-and-chilling/rapid-surface-chilling/rapid-surface-chilling.html
[65] http://iapreview.ars.usda.gov/research/publications/publications.htm?seq_no_115=297845
[66] http://www.linde.co.uk/en/news_and_media/press_releases/news_20130910.html

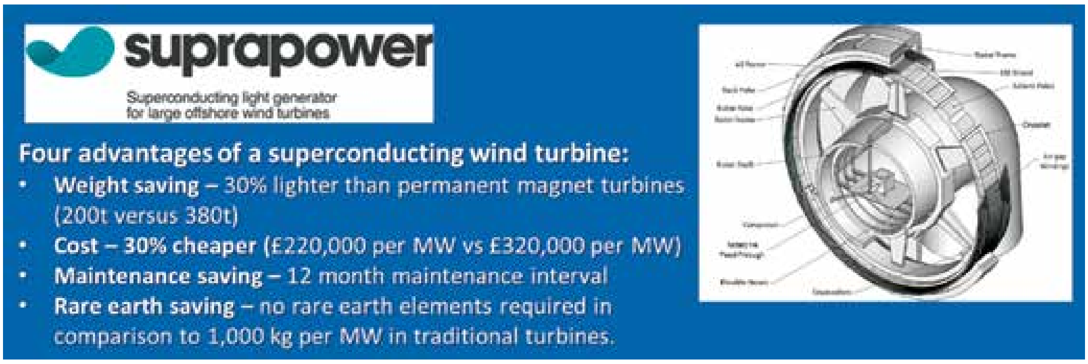


Figure 6.1: Four advantages of a superconducting wind turbine

Superconducting wind turbine generators

6.4. Higher power offshore wind turbines reduce the capital and operational costs per megawatt (MW) generated. However, providing much higher power turbines increases the technological and logistical challenges of construction. Superconducting coils can offer a way of substantially reducing the weight and size. Copper wire in the windings of the motor is replaced by superconducting wire, cooled cryogenically to temperatures such as 20 Kelvin.

6.5. The SUPRAPOWER[67] project is a €5.4 million EU FP7 research project to design an innovative lightweight 10 MW offshore wind turbine based on a superconducting magnesium diboride (MgB2) generator. The University of Southampton is one of nine partners in the SUPRAPOWER consortium drawing upon its expertise in cryogenically-cooled super-conductors. The superconducting turbine under development has four advantages over traditional wind turbines as shown in Figure 6.1.

6.6. The cost of offshore wind turbines installed is currently £3.1 million per MW with 20% of this cost, £620,000, relating to the turbine itself including gearbox and power converter[68], with just over 50% of this cost (i.e. £320,000) relating to the power converter alone. The superconducting power converter is expected to cost £220,000 suggesting a saving of £100,000 per MW. It is assumed that other costs, such as gearbox and blades, remain the same, even though direct drive superconducting turbines could, in time, replace the need for a gearbox. No account is taken of savings in operating costs that may result from improved reliability.

6.7. There is 36 gigawatt (GW) of offshore wind-power in development around the UK[69], and the UK is a world leader in offshore wind. If, on the basis of a conservative estimate, one-third of these used were cryogenically-cooled superconducting turbines, the saving to UK industry would be £1.2 billion. Globally, an additional 278GW of capacity is predicted by 2018[70]. Assuming one-third of these were to use superconducting turbines, the **savings to global industry could be £9.3 billion versus current costs.**

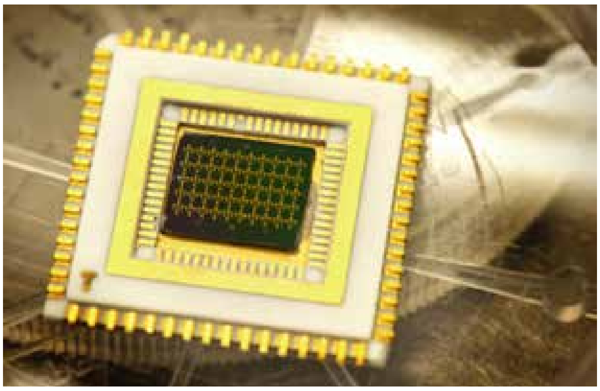
6.8. Within industry, the expectation is for overall costs to fall by 10% by 2018 or 23% by 2023 to £2.4 million per MW. Once in production, superconducting turbines could provide 3.2% of that expected saving thus making a major contribution to the viability of offshore wind.

Quantum technologies

6.9. **Cryogenic on-chip cooling:** In late 2014, researchers[71] published a paper[72] describing how they had successfully created a device that cools itself down to a cryogenic temperature (-228C) without liquid nitrogen or helium being used for external cooling. The chip itself remains at room temperature, while a

[67] SUPRAPOWER. SUPerconducting, Reliable, lightweight, And more POWERful offshore wind turbines
[68] Offshore Wind Project Cost Outlook (2014).
[69] RenewablesUK
[70] Global Wind Energy Council
[71] Pradeep Bhadrachalam, Ramkumar Subramanian, Vishva Ray, Liang-Chieh Ma and Seong Jin Koh from the University of Texas Arlington, and Weichao Wang, Prof. Jiyoung Kim and Prof. Kyeongjae Cho from the University of Texas Dallas.
[72] Nature Communications 5, Article number: 4745 doi:10.1038/ncomms5745 Received 3/3/2014, Accepted 18/7/ 2014 and Published 10/9/ 2014.

quantum well[73] within the device cools the electrons down to cryogenic temperatures. This development could enable electronic devices that consume ten times less energy than current devices, so this is an important development. In addition to potential commercial applications, there are many military uses for the technology. Batteries weigh a lot, and less power consumption reduces the battery weight of electronic equipment that soldiers are carrying, which will enhance their combat capability. Other potential military applications include electronics for remote sensors, unmanned aerial vehicles and high-capacity computing in remote operations. This achievement represents a technological breakthrough, tested and proven in the laboratory. The next steps are to achieve these cryogenic temperatures with actual electronic devices[74] and later on an industrial and large scale.



Credit: www.extremetech.com

6.10. **Quantum Computing:** Creating, controlling and exploiting the ultra-low temperature environment, and hence cryogenics, is crucial for the research and development of quantum-enhanced devices[75]. As mentioned in section 5 of the report in paragraph 5.15, STFC is involved in a joint project between Oxford Instruments and the University of Cambridge to develop platform technology for quantum computing. Furthermore, a new £120 million national network of Quantum Technology Hubs, that will explore the properties of quantum mechanics and how they can be harnessed for use in technology, is being funded by EPSRC, in conjunction with Innovate UK and other partners. This is part of the £270 million investment in the UK National Quantum Technologies Programme, in the Autumn Statement 2013. The four hubs announced in November 2014, will be led by Birmingham, Glasgow, Oxford and York universities[76].

[73] A quantum well is a very narrow gap that allows electrons to pass between two semiconducting materials, until they hit the gap (the well). Only electrons with specific characteristics can cross the boundary, in this case, only electrons with very low energy (i.e. cold electrons).
[74] http://www.extremetech.com/extreme/189999-on-chip-quantum-wells-create-cryogenic-electrons-computers-that-consume-10x-less-power
[75] Quantum computing effectively enables rapid performance of calculations by taking advantage of distinctive quantum-level properties of particles. The benefits of cryogenic, quantum well-cooled electrons are that they allow for the creation of electronic devices that consume less energy than current devices. Cooling has other advantages, some of which are: lower lead resistance and higher mobility in metals and semiconductors that allow higher operating speed for semiconductor chips; and, at sufficiently low temperatures access to the unique capabilities of superconducting electronics.
[76] http://www.epsrc.ac.uk/newsevents/news/quantumtechhubs/

7. Conclusions

7.1. The main objectives of this study have been to capture the economic and wider impacts of STFC's capabilities and investment in cryogenics and demonstrate the importance and contribution of cryogenics to the UK economy.

7.2. A combination of methods has been deployed to meet the objectives of the study:

- A mainly quantitative approach has been followed to capture the economic impact of cryogenics on the UK economy.
- This has been complemented by qualitative research, leading to the production of a selection of case studies illustrating STFC's unique role in cryogenics-related activity in the UK, and demonstrating both the impact of the technology in specific sectors to date, and its role in the advancement of research and potential applications. These case studies represent only a sample of the work funded and supported by STFC and its predecessors over the last 30 years.

7.3. This work has been based on extensive desk-based research to map out STFC's cryogenics capabilities and the relationship of activities to various economic sectors and other areas of research. Information has been collected on values and types of funding, areas and stages of scientific activities, key institutions, staff and scientists involved in cryogenics, and any consultative and collaborative activity with other research establishments and industry partners. A series of consultations were also conducted with key personnel within STFC, as well as external stakeholders, and scientific and industrial collaborators.

7.4. This study has shown that cryogenics as an enabling technology is widely applied in different fields of science and economic activity and it is very likely to be found in approximately 17% of the broad sectors representing the UK economy (based on SIC codes). Isolating and measuring the economic impact of such an enabling technology, however, poses a number of methodological challenges. This includes a lack of consistent pathways to impact for cryogenic applications (current and potential) and limited specific management and financial information that captures the nature and extent of this technology as a specific 'input' into a technological application's or scientific exploration's pathway to impact.

7.5. Nevertheless, a number of resources have been utilised, and assumptions have been made and tested with key stakeholders, in order to arrive at estimates of the financial and economic impacts. On the basis of these, the study estimates that:

- Cryogenics-related economic activities directly employ around 1,500 employees across the UK. These generate approximately £170 million GVA for the UK (direct economic impact/2014 figures).
- Taking into account multiplier effects, the total (direct and indirect) GVA contribution of cryogenics-related activities to the UK economy is estimated at around £324 million.
- On the basis of these calculations, cryogenics-related economic activities could contribute between £1.6 billion and £3.3 billion to the UK economy in the next 10 years.

7.6. Furthermore, STFC's cryogenic teams also make a contribution to the UK economy through operational impacts, i.e their employment (direct economic impact) and spending of their salaries within the economy (induced economic impact). It is estimated that 135 FTEs are fully involved in cryogenics-related activities within STFC and their operational impact on the UK economy is an estimated £11 million per annum.

7.7. The case studies have shown that STFC's role and significance for this technology goes far beyond its operational impact. The evidence reviewed for this report shows that STFC is the key sponsor of publicly-funded support for this technology and has played a unique role to date in developing the c£324 million cryogenics sector in the UK, particularly in the development of new high-value technologically challenging areas of cryogenics. STFC has been at the forefront of collaborations requiring cryogenics expertise, supporting projects of global significance, e.g closely working with the European Space Agency and NASA, and contributing to building the UK's international reputation in scientific and technological excellence but also UK companies' competitive position in the global market.

7.8. Furthermore, STFC's cryogenics capabilities make a significant contribution to the Government's agenda of knowledge generation by the UK research base and of higher, specific and wider skills development (workforce and researchers) for the improvement of the UK performance globally – economically and in terms of well-being. For example:

- Research, technical and business skills deployed by STFC centres are world-class as demonstrated by the case studies.
- The role of STFC in supporting the generation of intermediate, technical skills and expertise in cryogenics-related areas is also particularly valuable, considering that trying to source specialist cryogenics expertise is difficult.

7.9. STFC's continuous support has been pioneering in developing cryogenic technologies that are too risky, at early stage, or commercially uncertain to be supported by private investment. In each case it is not just funding innovation, and creating the right conditions for it, but also envisioning the opportunity space, engaging in the most risky and uncertain early research, and overseeing the commercialisation[77]. In this regard, STFC's partnerships with industry are helping to support 'open technology' and further technological commercialisation for the benefit of the UK economy. For example, STFC's testing facilities are available to the industry (including SMEs) and STFC helps to foster small business research and innovation, providing leading-edge laboratory space for high-tech SMEs to improve their efficiency and competitiveness.

7.10. STFC is also championing local and regional economic development and inward investment with a cryogenics infrastructure that has been developed around RAL and the other STFC facilities in the UK, comprising everything from global corporations to sought-after niche expertise in industry and scientific thinking and advancement. This infrastructure is an important anchor for further existing business expansion and additional inward investment.

7.11. It has not been possible, however, to quantify the exact contribution and value-added of the STFC investments to the UK economic impact of cryogenics. The key issue in capturing the full economic impact of STFC's contribution is that, as this is a technology underpinning basic research and complex scientific explorations that are funded by STFC as a whole project, it is not always possible to isolate the exact allocation of funding to this specific technology (equipment and/or expertise of teams/individuals). Furthermore, financial and management data are in general collected to meet wider organisational information requirements, rather than in a manner that would be fit for evaluation purposes, i.e clearly demonstrating the pathway of investment/budget to itemised expenditure but also revenue at process, technology and beneficiary levels.

[77]http://www.demos.co.uk/files/Entrepreneurial_State_-_web.pdf

Appendix A - List of abbreviations

ALMA	Atacama Large Millimetre Array
ASD	Applied Science Division
ASTeC	Accelerator Science and Technology Centre
ATLAS	A toroidal LHC apparatus
ATSR	Along Track Scanning Radiometer
BCC	British Cryogenics Council
CERN	Conseil Européen pour la Recherche Nucleaire -European Organisation for Nuclear Research
CES	Cryogenic energy storage
CCFE	Culham Centre for Fusion Energy
CIM	Centre for innovative manufacturing
CLF	Central Laser Facility
EDM	Electric Dipole Moment
ESA	European Space Agency
EPSRC	Engineering and Physical Sciences Research Council
ESS	European Spallation Source
FSA	Food Standards Agency
FTE	Full-time equivalent
GM	Gifford McMahon
GVA	Gross value added
GW	Gigawatt
He	Helium
ICT	Information and communications technology
ILL	Institute Laue-Langevin
IOP	Institute of Physics
IQC	Institute for Quantum Computing
IT	Information technology
JWST	James Webb Space Telescope
LAES	Liquid air energy storage
LCD	Liquid crystal display
LED	Light-emitting diode
LH_2	Liquid hydrogen
LHC	Large Hadron Collider
LHe	Liquid helium

LISA	Laser Interferometer Space Antenna
LNG	Liquified natural gas
MICE	Muon Ionisation Cooling Experiment
MIRI	Mid infrared instrument
MIT	Massachusetts Institute of Technology
MOONS	Multi-object optical and near-infrared spectrographs
MRI	Magnetic resonance imaging
MW	Megawatt
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NHS	National Health Service
NIF	National Ignition Facility
NPV	Net present value
O_2	Oxygen
OLED	Organic light-emitting diode
RAL	Rutherford Appleton Laboratory
RF	Radio frequency
RGF	Regional growth fund
SIC	Standard industrial classification
SLSTR	Sea and Land Surface Radiometer
SME	Small and medium sized enterprises
SRF	Superconducting radio frequency
SST	Sea surface temperature
STEM	Science, technology, engineering and maths
STFC	Science and Technology Facilities Council
THz	Terahertz
UK ATC	UK Astronomy and Technology Centre

A Report for the

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