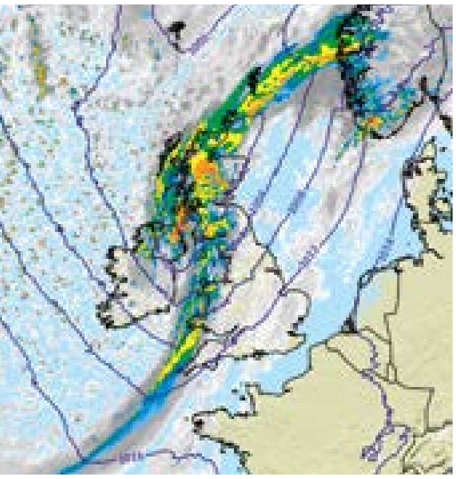
UK Research and Innovation

The UK's research and innovation infrastructure: opportunities to grow our capability




FAAM


BIG DATA
MATERIALS SCIENCE
CATAPULT
SYNCHROTRON
UK's Research and Innovation Infrastructure
2030
BIO IMAGING

Contents

Front cover image credits: Top - Met Office, Middle - UK Research and Innovation .
Inside cover illustration: Helen Towrie, UK Research and Innovation.

Foreword

We are at one of the most important, exciting and challenging times in the history of global enterprise. Powered by new technologies, the way we live our lives is being transformed across the world. The UK is extraordinarily well-placed to benefit from this new industrial revolution. We are an open, enterprising economy, built on invention, innovation and competition.

Research and development has a central role to play in responding to the challenges we face and taking full advantage of the opportunities they offer. It is core to the successful delivery of the four Grand Challenges identified in the UK's Industrial Strategy, which aim to put the UK at the forefront of tackling global seismic transitions and grow the industries of the future. Recognising this transformational potential, the government has positioned research and development at the heart of the Industrial Strategy set an ambitious target to increase total investment in Research and development to at least 2.4% of Gross Domestic Product by 2027.

As part of the approach to realising the government's Industrial Strategy, UK Research and Innovation was commissioned to develop a research and innovation infrastructure roadmap. This report provides an assessment of the future infrastructure landscape and strategic themes which could create a step-change in the UK's capability over the next ten years. The report will be used as a strategic guide to inform future investment decisions across the landscape. Our aspirations are ambitious, but delivery of the Industrial Strategy and 2.4% goal requires this.

The UK's global stature in research and innovation is underpinned by a long history of funding world-class research and innovation infrastructure. This infrastructure brings together global talent from across disciplines and economic sectors to tackle society's most complex challenges and drive economic growth. Research and innovation infrastructure is not only funded through UK Research and Innovation and its councils. Many public sector organisations support research and innovation capability within the UK and we would like to recognise the contribution and support from many of these over the course of this programme. Close collaboration with international partners also provides the UK research and innovation community with access to critical capability all around the world.

This programme has been an ambitious one; the UK has never undertaken an exercise of this scale before. We recognise that, within the time available, it has not been possible to capture everything we would have liked and we are grateful for the input that many expert stakeholders have made to the process. This report will inform our approach to the UK Research and Innovation infrastructure portfolio and provides a solid basis for building our understanding and exploring particular issues in more depth.

Professor Mark Thomson
Executive Chair of the Science and Technology Facilities Council (STFC) and Senior Responsible Officer for the UK Research and Innovation infrastructure roadmap programme

Sir Mark Walport
Chief Executive Officer of UK Research and Innovation

Executive summary

This report provides an assessment of the future research and innovation infrastructure landscape. It identifies potential opportunities to create a step-change in the next-generation of infrastructure capability and options for resulting investment and is intended to guide decision-making and identification of priorities to 2030.

Research and Development (R&D) has a central role to play in driving economic growth. It is core to the successful delivery of the four Grand Challenges identified in the Industrial Strategy, which aim to put the UK at the forefront of tackling global seismic transitions and grow the industries of the future. The ability to develop new ideas and deploy them is one of the UK's greatest strengths. Today the UK is globally recognised as a leader in research and innovation, having the most productive science base in the G7 based on field-weighted citations impact[1] and research papers produced per unit of R&D expenditure[2]. Every £1 spent on public R&D unlocks £1.40 of private R&D investment[3], together delivering £7 of net-economic benefit to the UK[4].

We are highly successful in translating knowledge into real-world societal, economic and international benefit – estimates suggest that more than half of the UK's future productivity growth will be driven by the application of new ideas, research and technology to create new processes, products and services[5].

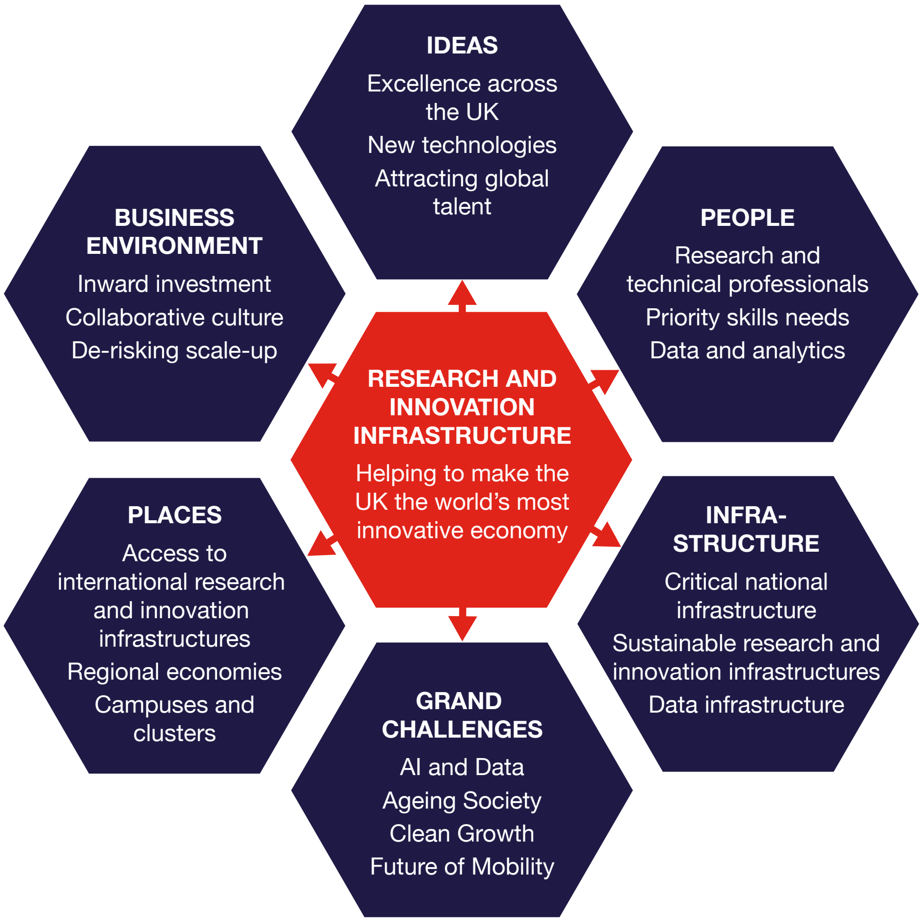


Figure 1. The Industrial Strategy sets the ambition for the UK to be the world's most innovative economy. Research and innovation infrastructures contribute across the strategy and to each of the Grand Challenges.

These successes are in large part founded on a network of internationally competitive, high-quality and accessible research and innovation infrastructures. This programme has defined research and innovation infrastructure broadly, ranging from big physical research facilities such as synchrotrons, research ships and scientific satellites, to knowledge-based resources such as scientific, cultural or artistic collections, archives and scientific data, data and computing systems and communication networks, test beds, demonstrators and living labs which can simulate how innovations might work in the real-world. Our analysis of the UK landscape has revealed over 500 nationally and internationally significant infrastructures with a breadth of expertise across sectors with 92% of these infrastructures working across multiple domains. Over three quarters of infrastructures in our analysis report that they work with business and 42% with public policy. Evaluation of individual infrastructures demonstrates the wider impacts on the economy:

- The European Molecular Biology Laboratory – European Bioinformatics Institute (EMBL-EBI) at Hinxton manages public life science data on a very large-scale. EMBL-EBI data and services provide an estimated £1 billion per annum of efficiency gain benefits for its users (equivalent to more than twenty times the direct annual operational cost of EMBL-EBI). In addition, it underpins future economic impacts worth £335 million annually[6]
- A recent evaluation of forty-one mid-scale research infrastructure case studies estimated an average return on investment of £3.40 per £1 spent[7]
- The ISIS Neutron and Muon source based at the Harwell Campus is expected to deliver £1.4 billion of net economic benefit based on its work to 2014, with a further £1.4 billion of economic benefit predicted up to 2030[8]
- Estimates suggest the Babraham Research Campus (supporting early stage bioscience) has helped create 6,673 high value jobs and generated £298 million of value for the UK[9]

Between 2015/16 and 2020/21, the Department for Business, Energy and Industrial Strategy (BEIS) and UK Research and Innovation have committed to spend over £7.5 billion of capital funding on research and innovation infrastructure[i].

We want to build on this tradition of innovation and on our current strengths. The Industrial Strategy[10] sets the ambition for the UK to be the world's most innovative economy and the government is committed to raise total R&D investment to at least 2.4% of Gross Domestic Product (GDP) by 2027. Linked to the Industrial Strategy are four Grand Challenges that ensure a clear focus on areas of existing strength and global opportunities: putting the UK at the forefront of the Artificial Intelligence (AI) and data revolution; maximising the advantages for UK industry from the global shift to Clean Growth; becoming a world leader in shaping the Future of Mobility; and harnessing the power of innovation to help meet the needs of an Ageing Society.

This report identifies potential opportunities to strengthen and expand our already impressive national and international infrastructure capability, on the way to achieving our wider ambitions. It identifies opportunities to create a step-change in the next-generation of infrastructure capability – both within the UK and through international partnerships – and options for resulting investment in key thematic areas (Figure 2). Among others, these include:

- Developing new highly advanced technologies to explore the workings of the Universe and planetary climate systems down to individual cells and the atomic structure of materials
- Using new technologies to enhance access to our unique museum collections, to harness our heritage for future generations
- Achieving a step-change in technological capability and the availability of data – from next-generation sensors to the exascale computing challenge – to observe, model, predict and simulate, and also to engage people, unlocking information about our planet, our society and ourselves
- Developing new ways to test and de-risk technologies or ideas which are close to market application

i This includes allocations through the Science Capital Ringfence and to Innovate UK's Catapults programme

Biological sciences, health and food

- Multiscale biology, biological imaging, structural biology and 'omics technologies
- Biosecurity for the life sciences
- Human phenotyping (at depth and scale)
- Population data for health research
- Food safety and nutrition
- Advanced animal genomics, developmental biology and breeding infrastructures
- Plant genetics, pathology, phenotyping and agri-technology
- Innovation in biotechnology and biomedical science
- E-infrastructure for life sciences

Physical sciences and engineering

- Understanding the Universe
- Novel technologies for next-generation infrastructures
- Catalysing productive growth (manufacturing, stress engineering, quantum technologies)
- Technologies to improve health
- Future transport solutions
- Enhancing future connected digital technologies

Social sciences, arts and humanities

- New data infrastructures to inform the major challenges of our time, e.g. productivity, health and wellbeing
- Driving innovation and growth in existing infrastructures, including the future of data access and analysis
- Creative industries and design
- Unlocking potential of our cultural heritage
- Future policy enablers

Environment

- Sentinels of change – structures focused on global change such as fleets of underwater autonomous vehicles
- Labs for observing – integrated networks of sensors and instruments
- Labs for simulation and prediction – next-generation super computing
- Labs for data analytics and machine learning

Energy

- Whole energy systems – including energy transmission and use
- Fuel cells and hydrogen
- Energy storage
- Renewable energy sources
- Alternative fuels
- Nuclear energy – fission and fusion
- Carbon capture and storage

Computational and e-infrastructure

- Supercomputing
- Data infrastructure for storing and managing access to vast quantities of data
- Cloud computing
- The National network to connect universities and research organisations
- Authentication, Authorisation and Accounting Infrastructure (AAAI)
- Software and skills

Figure 2. Key themes across sectors.

In developing this report, key themes emerged early in the process. These are at the heart of our ambition to enhance the UK's research and innovation infrastructure capability and create an interconnected landscape:

The importance of investing in the talent pipeline

To develop the researchers, innovators, engineers, technical professionals and other specialist roles needed to build, maintain and use our infrastructure, we need a strong and interconnected talent pipeline across all sectors and across career stages, and we must offer effective career support. This pipeline must also be flexible, to identify and meet skills and training needs as new technologies develop or as gaps emerge when supply exceeds demand in both business and academia. Of immediate importance is the provision of technical professionals with digital, data science and AI skills.

In these areas, demand already exceeds supply and shortages will become more acute in response to the infrastructure requirements described throughout this report. Labour market analysis commissioned by the Royal Society found that one in two job adverts for data scientists require machine learning, and one in eight demand AI – an increase of more than 3,000% and 7,000% respectively since 2013[11].

In developing its talent and skills strategy, UK Research and Innovation is taking an overarching view on what a healthy and thriving future research and innovation workforce will look like and the interventions required in the context of delivering the 2.4% target.

The provision of robust and effective e-infrastructure

E-infrastructure is an essential and pervasive requirement and there is certainty of growth in demand and rapid development in technology in both business and academia. To remain at the forefront of research and innovation the UK needs a long-term, strategic programme of investment in e-infrastructure. This infrastructure will need to be both diverse, to reflect the different needs of academia and business, and integrated to ensure effective use of resources. E-infrastructure is not just computers and data storage hardware, but also includes the software, networks, security and standards without which most modern research would not be possible.

Our ambition is to host a world-class national exascale supercomputing facility by the middle of the next decade and to accelerate data-intensive research by providing increased capacity and capability across the e-infrastructure ecosystem.

Changing economic context, new technologies and practices are transforming the way research and innovation is undertaken

The world is on the cusp of a 'fourth industrial revolution', with developments in 'big data', digitisation, synthetic biology and AI driving a change in the nature of the economy. Venture capital investment in the UK's growing AI sector leapt almost sixfold from 2014 to 2018, with funding amounting to almost as much as in the rest of Europe combined, and investment in UK AI start-ups reached US$1.3 billion in 2018[12]. The 'lab of the future' could look and feel very different to today as the challenge of increasing volumes of data and the opportunities from AI and machine learning impact across all disciplines and sectors. For example, enhancements in modelling and simulation capability coupled with real-world experimentation are improving our ability to test and validate new ideas, products and processes at scale, driving economic growth. The UK has considerable strengths in 'big data' science which we can build on in future years. Yet this data explosion also brings challenges for infrastructures in successfully manipulating, curating, storing and using massively abundant data sets across differing formats and types, and across distributed networks. UK Research and Innovation recognises more work is needed in this area and will take this forward.

In addition, new business models are leading to greater outsourcing of R&D to specialist R&D services and innovative small- and medium-sized enterprises, even as the divide between services and manufacturing becomes more blurred[13]. The pace of this change is increasing, driving more complex interactions and challenging the way researchers and innovators work[14]. Business and researcher needs increasingly drive a requirement to work at scale and across disciplines challenging traditional mechanisms of quality assurance.

The disruptive nature of these changes can in part be addressed through the development of demonstrators and other – near-market projects to test solutions in real-life conditions: those designed to take a 'whole systems' approach and those focused on de-risking or scaling-up implementation. This includes, for example testing how energy technologies might work at scale and trialling development of autonomous vehicles or novel approaches to the manufacture of pharmaceuticals.

Operating at scale: building and enhancing national and international connections

Cross-disciplinary and cross-sectoral working at all scales enables more productive and efficient use of infrastructure.

Places are at the heart of the Industrial Strategy. At a local level, cooperation between geographically close research and innovation infrastructures and businesses can create a cluster effect that leads to enhanced innovation and partnerships. This critical mass can attract new businesses and people, which fosters further growth, boosts local employment and enables cross-sector working. Over time, this can create an innovation infrastructure that is greater than the sum of its parts with a strong reputation, which can be leveraged to attract further business.

At a national level, we need to invest in strategic infrastructure networks and forge better linkages between existing infrastructure. This distributed infrastructure can be focused around a core technology or methodology, or a research topic or application. This requires a proactive community that is fully engaged in scoping the requirements. The rewards are the potential to operate at greater scale; more effective use of resources; more coherent ways to develop common skill sets; sharing of good practice; and fostering innovation in methods which inform the planning of subsequent infrastructure.

The Smith Review demonstrates the importance of international collaboration. Many research and innovation infrastructures are too big, complex or expensive for a single country to build and manage alone. Creation of international partnerships enables research and innovation at scale, whether it be multinational physical science facilities, continent-wide distributed e-infrastructure networks, or global heritage databases and knowledge transfer processes. The UK needs to remain an active partner internationally to continue to benefit from the sharing of knowledge, expertise, data and capability across organisations, borders and continents.

Sustainability of infrastructures

Research and innovation infrastructures are long-term investments, often spanning decades from planning through development to operation. Many evolve or are repurposed over time to respond to demand from users or the disruptive effect of new technologies before eventual decommissioning. For others their value increases over time as data accumulates. Crucially, sustainability requires stable financial support and a long-term investment plan. 60% of infrastructures in our analysis have an expected operational lifetime of over twenty-five years but only 41% felt able to plan one to three years ahead.

Budgets will always be finite and, as the UK expands its research and innovation infrastructure toward the 2.4% target, we must ensure appropriate tensioning between development and investment in new capability on the one hand, and the requirement to maintain, develop and decommission existing infrastructures on the other.

In addition, investment is required in 'continuous improvement' to underpinning technologies, methodologies and techniques such as sensor technology, imaging, data analysis methodologies and curation techniques.

Next steps

This report and accompanying Landscape Analysis provide an overview and assessment of existing UK infrastructure and key international facilities in which the UK participates. This report is intended as a strategic guide to inform future investment decisions and identification of priorities for the next-generation of infrastructure to 2030. In the context of the goal to reach at least 2.4% of UK GDP invested in R&D by 2027, this report is deliberately ambitious and provides an overview of potential infrastructure opportunities that could lead to a step-change in the capability available to researchers and innovators over the next ten years. We have not attempted to prioritise the opportunities described here.

Ultimately, future funding to develop existing infrastructures or create new capability set out here will be dependent on strategic investment decisions and the availability of funding from a range of organisations including the government and UK Research and Innovation. UK Research and Innovation is establishing a clear approach to managing its infrastructure portfolio to address issues of sustainability and continue to ensure value for public investment. We will use this report to inform the prioritisation of infrastructure investments (Figure 3) alongside additional work to explore implementation, costs and feasibility of projects and to define and scope ideas which are at earlier stages of development in anticipation they can feed into the portfolio over time.

We are grateful for the substantial support and input from across academia, representative bodies and learned societies, business networks, charitable organisations, universities, Public Sector Research Establishments (PSREs), the Catapult network, government departments, funding bodies, the Devolved Administrations and UK Research and Innovation's extensive network of advisory committees. The programme has also drawn on an Advisory Board, which includes representatives from UK Research and Innovation Councils, the Department for Business, Energy and Industrial Strategy (BEIS), BEIS-funded PSREs, Universities UK, the Association for Innovation, Research and Technology Organisations (AIRTO), Devolved Funders and the Royal Society. We are also grateful for insights from colleagues responsible for the development of roadmaps in other countries and from the European Strategy Forum on Research Infrastructures (ESFRI), and to international representatives who participated in a workshop at the 2019 Annual Meeting of the American Association for the Advancement of Science (AAAS).

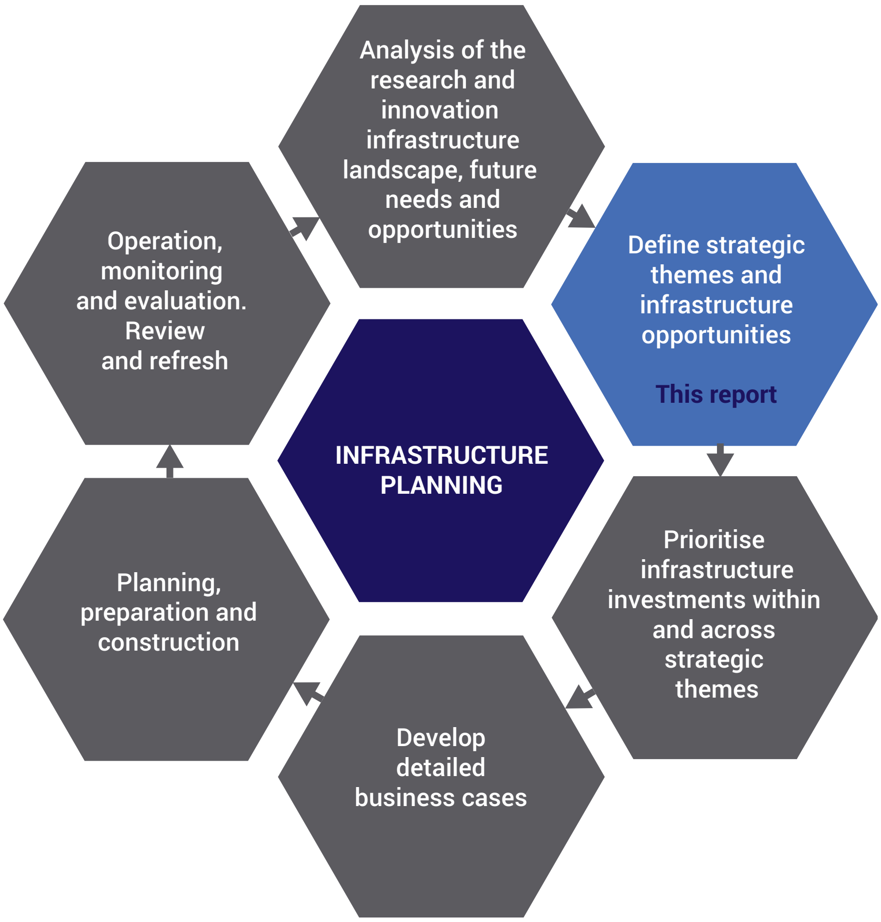


Figure 3. Overview of the infrastructure planning process.

Chapter 1: Strategic context

The Industrial Strategy[10] sets the ambition for the UK to be the world's most innovative economy and the government is committed to raise total R&D investment to 2.4% of GDP by 2027. Our ability to innovate – to develop new ideas and deploy them – is one of the UK's great historic strengths, bringing significant benefit to the economy and society. Research and innovation infrastructures bring together talent from the public and private sectors and across disciplines to tackle society's most complex challenges and generate knowledge and capability critical to UK policy, security and wellbeing. This includes the Grand Challenges set out in the Industrial Strategy: putting the UK at the forefront of the AI and data revolution, maximising the advantages for UK industry from the global shift to Clean Growth, becoming a world leader in shaping the Future of Mobility, and harnessing the power of innovation to help meet the needs of an Ageing Society.

Estimates suggest that over half of the UK's future productivity growth will be driven by the application of new ideas, research and technology to create new processes, products and services[3]. This is expected to increase over time as the pace of technological change increases the importance of knowledge-based capital. The UK has the most productive science base in the G7, ranking first for field-weighted citations impact (a measure of research quality)[1,15] and number of research papers produced per unit of R&D expenditure[2]. The UK also ranks fifth in the Global Innovation Index[5,16]. Every £1 spent on public R&D unlocks £1.40 of private R&D investment[3], together delivering £7 of net-economic benefit to the UK[4]. This includes investment from overseas, helping to make the UK a location of choice for businesses at the cutting edge of innovation and technology; the UK attracts more overseas investment in R&D than many other countries[17].

This research productivity and inward investment are founded on the availability of internationally competitive, high-quality infrastructure. Access to world-leading infrastructures supports research and innovation activity at all scales, from individual investigators to large multinational collaborations. They act as a magnet to international talent and users, contribute to local and national economies, and generate knowledge and capability critical to UK policy, security and wellbeing. Many link to the development of key sectors of the economy, including those supported through Sector Deals as part of the Industrial Strategy.Others perform vital functions for government policy-makers including statutory functions, informing public policy, improving public services and supporting resilience and response to emergencies. Evaluation of individual infrastructures demonstrates these real-world impacts:

- The European Molecular Biology Laboratory – European Bioinformatics Institute (EMBL-EBI) at Hinxton manages public life science data on a very large-scale. EMBL-EBI data and services provide an estimated £1 billion per annum of benefits for its users (equivalent to more than twenty times the direct annual operational cost of EMBL-EBI). In addition, it underpins future economic impacts worth £335 million annually[6]
- A recent evaluation of 41 mid-scale research infrastructure case studies estimated an average return on investment of £3.40 per £1 spent[7]
- The ISIS Neutron and Muon source is expected to deliver £1.4 billion of net economic benefit based on its work to 2014, with a further £1.4 billion of economic benefit predicted up to 2030[8]
- Estimates suggest the Babraham Research Campus (supporting early-stage bioscience) has helped create 6,673 high value jobs and generated £298 million of value for the UK[9]

Case Studies
Delivering the Industrial Strategy Grand Challenges

AI and DATA
Using machine learning and statistical methodology to reduce the impact of air pollution

Poor air quality in cities poses a significant threat to health and life expectancy. In London, it is estimated that more than 9,000 Londoners die prematurely each year due to air pollution. Researchers from The Alan Turing Institute, in collaboration with the University of Warwick, are working with the Greater London Authority to develop machine learning algorithms, data science platforms and statistical methodology to better integrate and analyse sensor data on air pollutants. As part of navigation specialists Waze's Connected Citizens Program, the project can access real-time traffic data which, in conjunction with Transport for London (TfL) data, allows for a more accurate picture of levels of pollution across London. This research is being used to develop a mobile-friendly application programming interface that will provide rolling hyper-local forecasts of air pollution across London up to forty-eight hours ahead of time.

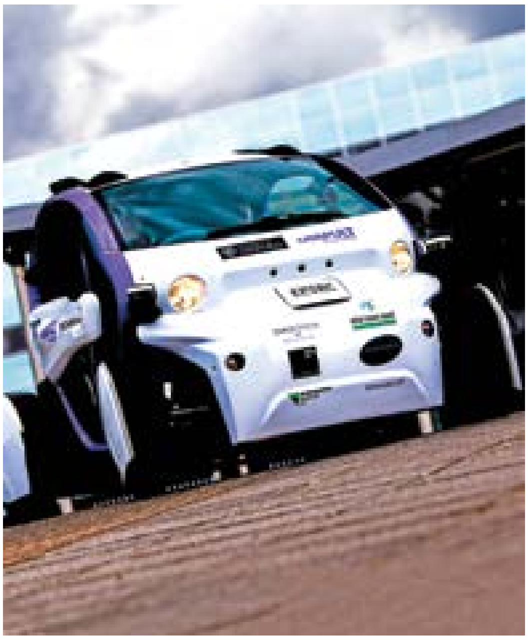
Rudy and Peter Skitterians Pixabay

AGEING SOCIETY
Age UK use Understanding Society study to create an Index of Wellbeing in Later Life

Age UK aims to measure the wellbeing of older people in the UK but, in the past, there was no single and coherent measure available. Researchers therefore used data from the Understanding Society study, the largest longitudinal household study of its kind, to create an Index of Wellbeing in Later Life. The index uses more than 200 possible wellbeing indicators and assigns weightings to signify their importance. Local branches of Age UK are using insights from the study to plan how to target their support services at people at risk of experiencing a low level of wellbeing.

FUTURE of MOBILITY

Testing driverless cars at UKAEA's state-of-the-art robotics technology centre



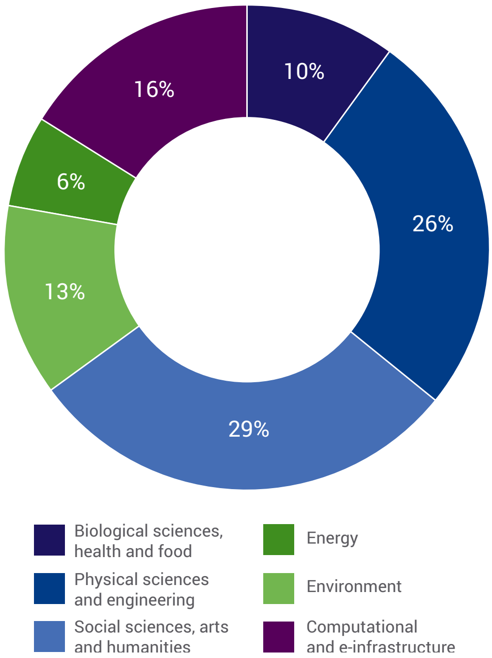
The UK Atomic Energy Authority's (UKAEA's) Remote Applications in Challenging Environments (RACE) facility is being used to test development of autonomous vehicles. Users include the DRIVEN consortium, who have used the site to carry out development work ahead of public demonstrations of autonomous vehicle technology in London and Oxford. The RACE facility provides a 10km test track of roads, junctions and roundabouts (complete with traffic lights and pedestrian crossings) to test the vehicles' ability to monitor and react to other vehicles, cyclists and people in realistic circumstances. The site will also include a dedicated 4G connection for autonomous vehicles operating onsite, electric vehicle charging, vehicle storage and drive-in autonomous vehicle pit lanes. The open-access facility is being delivered in partnership with Millbrook Proving Ground (part of the Spectris plc Group). The DRIVEN consortium is led by Oxbotica Ltd and includes AXA XL, Cicero Group, the Oxford Robotics Institute, Nominet, Oxfordshire County Council, Telefonica, TfL, the Transport Research Laboratory and UKAEA.

CLEAN GROWTH

World's first green energy storage demonstrator to deliver carbon-free power

The world's first green energy storage demonstrator is now live in the UK and features carbon-free fuel that can be stored or transported for later use. The project is a collaborative effort between Siemens, STFC, Oxford University and the University of Cardiff and is part of the Innovate UK Decoupled Green Energy project, funded with £1 million from UK Research and Innovation and approximately £500k from Siemens.

On-site energy storage is becoming increasingly attractive to organisations as there are times when the UK electricity grid is unable to accept all the wind power being generated across the nation. This means either the wind turbines are turned off or the electricity is used on site or stored. However, carbon-free chemical energy storage – including ammonia – has the potential to work alongside other storage methods and increase the infiltration of renewable power into our energy systems. The demonstrator project offers a way to decouple the supply of electricity from demand. It uses renewable electricity to obtain hydrogen from water via electrolysis, and nitrogen via air separation, to power the Haber-Bosch process to make ammonia. Ammonia produced in this way can be a completely carbon-free and practical bulk energy source. This demonstrator has proven that ammonia is a viable option and can help reduce carbon emissions from existing industrial processes, as well as provide a means for transporting and storing carbon-free energy in bulk.



Over **500** nationally and internationally significant infrastructures

A breadth of expertise: **92%** work across more than one topic domain

Three quarters work with UK business and **42%** with public policy organisations

Infrastructures employ just under **25,000** staff

Figure 4. The UK's extensive and diverse research and innovation infrastructure landscape.

The UK research and innovation infrastructure landscape is extremely diverse, from large-scale physical research facilities such as synchrotrons, research ships and scientific satellites, to networks of imaging technologies and knowledge-based resources such as scientific, cultural or artistic collections, archives, scientific data and computing systems, and research cohorts based on the participation of dedicated volunteers (Figure 4).

Between 2015/16 and 2020/21, BEIS and UK Research and Innovation have committed to spend over £7.5 billion of capital funding on research and innovation infrastructure[ii]. Additional public investment is also provided through other government departments and agencies, the devolved nations, local authorities and European programmes.

Planning for infrastructure requires consideration and anticipation of critical research and innovation requirements often decades ahead of actual use. In our Landscape Analysis[18], 60% of infrastructures have an expected duration of over twenty-five years and 78% over fifteen years. The path to 2.4% requires increased investment in the people and infrastructure needed to undertake R&D successfully. To deliver the 2.4% target, R&D investment in the UK will need to increase to around £70 billion in 2027, doubling in nominal terms[13]. This is in line with other countries' ambitions to grow investment in R&D. The vast majority of countries have experienced increasing R&D intensity since 2000. For example, Germany's R&D expenditure financed by government and domestic businesses was, respectively, 35% and 47% higher in 2016 compared to 2000[19]. It is now seeking to drive its R&D intensity to 3.5% of GDP by 2025. China has a target to reach 2.5% R&D investment by 2020[20] and France has a 3% target[21]. The US federal budget for research saw a notable increase in 2018/19, representing the largest increase in a decade[22]. The UK has a strong tradition of international collaboration and partnership and the proportion of UK research articles with an international partner doubled between 2000 and 2017[13]. It is vital this continues with opportunities to build on our international partnerships in future years.

ii. This includes allocations through the Science Capital Ringfence and to Innovate UK's Catapults programme.

Alongside these ambitions for growth, the changing economic context and new technologies and practices are transforming the way research and innovation is undertaken. The world is on the cusp of a 'fourth industrial revolution', with developments in 'big data', digitisation, synthetic biology and AI driving a change in the nature of the economy. Venture capital investment in the UK's growing AI sector leapt almost sixfold from 2014 to 2018, with funding amounting to almost as much as that in the rest of Europe combined and investment in UK AI start-ups reached US$1.3 billion in 2018[12]. The 'lab of the future' could look and feel very different to today as the challenge of increasing volumes of data and the opportunities from AI and machine learning impact across all disciplines and sectors.

The UK has considerable strengths in 'big data' science and a wealth of data assets and infrastructure. 'Digital twinning' and enhanced modelling and simulation capability alongside experimentation in the real-world improves our ability to test and validate new ideas, products and processes at scale. Adopting the principles of open discovery brings new ways of sharing and debating research, digitising museum collections provides resources to new users and the explosion in the use of social media and greater opportunities for citizen science are opening up new ways to design and conduct research. Underpinning technologies and techniques are increasingly relevant across disciplines with opportunities to share expertise and capability (Figure 5) and the recent Science Horizons Survey[iii] demonstrates the importance of frontier techniques in measurement and imaging, sensors and screening and modelling and simulation. New business models are leading to greater outsourcing of R&D to specialist R&D services and innovative SMEs alongside a blurring of the divide between services and manufacturing[13].

The pace of this change is increasing, driving interactions that are more complex and challenging the way researchers and innovators work and the skills they need[14]. There is an opportunity to create step-changes in our understanding of the world around us, to integrate understanding across disciplines in new ways and to develop new partnerships and business opportunities. Our future research and innovation infrastructure needs to play a part in driving and responding to these changes.

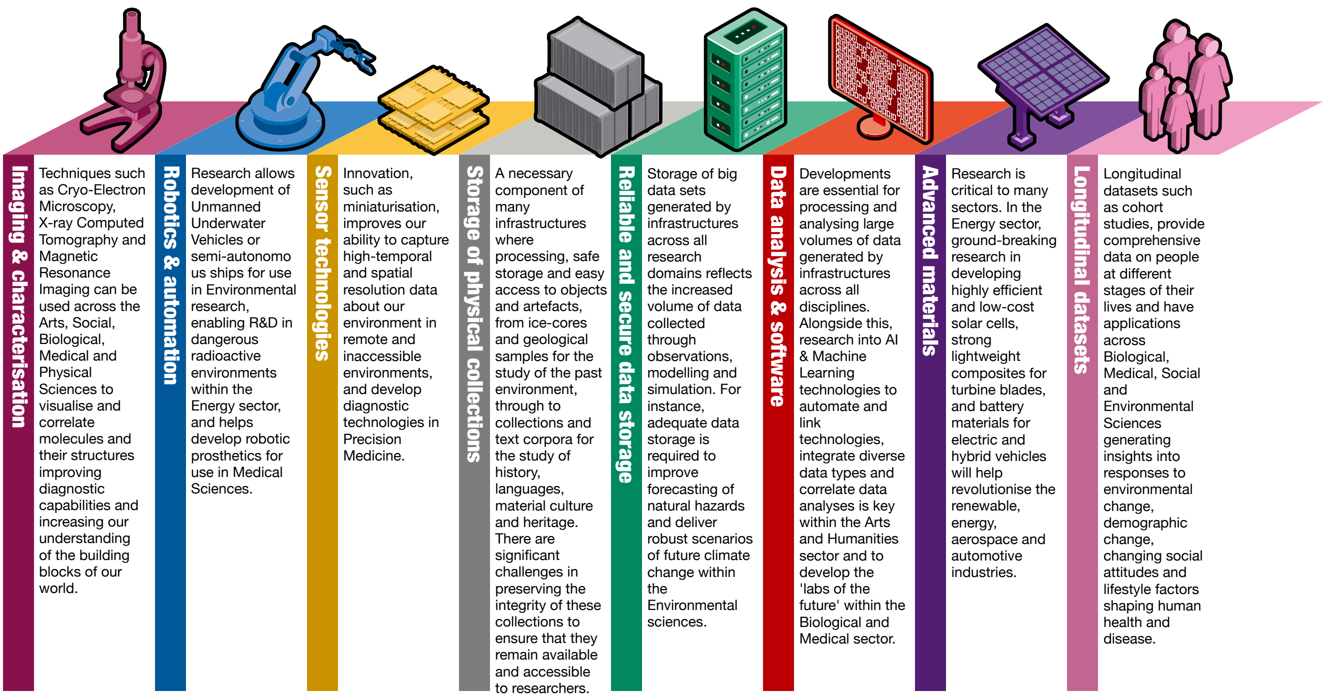


Figure 5. Common underpinning technologies and techniques identified through programme consultations.

iii Royal Society of Chemistry, Science Horizons research report: Leading-edge science for sustainable prosperity over the next 10-15 years, 2019

Chapter 2: Purpose of the Infrastructure Roadmap Programme

Many OECD countries develop research infrastructure roadmaps as tools to support strategic planning[23]. The UK has also undertaken similar exercises in recent years [24,25,26,27,28], taking an active part in the ESFRI prioritisation process for pan-European infrastructures[29]. However, the need to update and broaden our understanding of both current capability and future needs has been raised by both the House of Lords Science and Technology Select Committee[30] and the National Audit Office. UK Research and Innovation has undertaken an eighteen month exercise to produce this report and parallel Landscape Analysis[18]. This report provides an assessment of the future research and innovation infrastructure landscape. It identifies opportunities to create a step-change in the next-generation of infrastructure capability and options for resulting investment, and is intended to guide decision-making and identification of priorities to 2030.

2.1 Programme objectives

The objective of the UK Research and Innovation infrastructure roadmap programme is to create a long-term (until approximately 2030) research and innovation infrastructure roadmap based on an understanding of existing UK infrastructure (and key international facilities in which the UK participates), future needs (research, economic and social) and resulting investment priorities. In addition, the programme will seek to:

- Identify future research and innovation capability priorities
- Identify opportunities for increasing inter-connectivity
- Support development of UK Research and Innovation's overall long-term investment plan
- Promote the UK as a global leader in research and innovation
- Set out the major steps needed to reach the long-term vision as part of wider work to achieve the government's ambition to invest 2.4% of GDP invested in R&D by 2027

2.2 Scope and definition of research and innovation infrastructure

The term 'research and innovation infrastructure' can be interpreted in many different ways. For the first UK programme of this scale we have adapted the definition used by similiar international exercises and those in many other countries to also include innovation[31]:

'Facilities, resources and services that are used by the research and innovation communities to conduct research and foster innovation in their fields. They include: major scientific equipment (or sets of instruments), knowledge-based resources such as collections, archives and scientific data, e-infrastructures, such as data and computing systems and communication networks, and any other tools that are essential to achieve excellence in research and innovation.'

There is currently no commonly accepted definition of 'innovation infrastructure' so for this programme we have focused on '*facilities and assets that enable the development, demonstration and delivery of innovative (new to market) products, services or processes in business, public services, or non-profit sectors*'. This includes infrastructure aimed primarily at industry and set up explicitly to foster and commercialise innovation, such as the Catapult Centres, Innovation and Knowledge Centres, Centres for Agricultural Innovation and Innovation Centres in Scotland. It also recognises the wider role of infrastructure where academic researchers and businesses collaborate and of innovation- focused activities based within universities, PSREs or research and innovation campuses.

As with similar exercises undertaken in other countries, we are focusing on international and national-level activities that are open to a wide range of users to undertake excellent research and innovation. We are not seeking to capture or explore regional or local needs for infrastructure but recognise the importance of underpinning investment in smaller and mid-range facilities within universities and PSREs. Often funded through core capital budgets, institutions or project specific grants, such equipment and facilities provide the essential tools and fundamentals of a 'well-found' research establishment. Further details of scope and definition are set out in the Landscape Analysis[32].

We have also focused on infrastructure funded largely through public sector research and innovation funders. This means we have not sought to capture capability funded solely through private or charitable means. However, we recognise that partnership with the charity sector, and shared facilities with industry and public services such as the National Health Service (NHS), are also vital to the UK and many existing collaborations and partnerships already draw on this capability. For example, much clinical research and translation is reliant on the National Institute for Health Research (NIHR; England) funding for research capacity, NHS staff time and facilities. Future editions of this report could develop these areas further.

The work in this programme has been structured under the broad sectors used by the European Strategy Forum on Research Infrastructures (ESFRI) to support alignment of activities. These are:

- Biological sciences, health and food
- Energy
- Environment
- Physical sciences and engineering
- Social sciences, arts and humanities
- Computational and e-infrastructure

However, few infrastructures support a single sector even when using definitions as broad as these and we recognise that many infrastructures are multidisciplinary or interdisciplinary. This is described in more detail in the Landscape Analysis[18].

2.3 Developing this report

Figure 6 summarises the process used to develop the report. This included: analysis of the current UK research and innovation infrastructure landscape drawing on over 900 questionnaire responses[32]; reviewing existing literature and roadmaps within subject areas; a series of interviews and over thirty-five dedicated workshops and meetings involving over 800 experts; alongside advice from UK Research and Innovation's existing advisory networks, including UK Research and Innovation Councils, strategic boards and committees, and insights from parallel work to develop the UK Research and Innovation 2.4% roadmap[13] and Delivery Plans[33]. Our initial findings were published in a Progress Report[34] which we used to test emerging ideas and elicit further feedback, challenge and discussion before compiling this report.

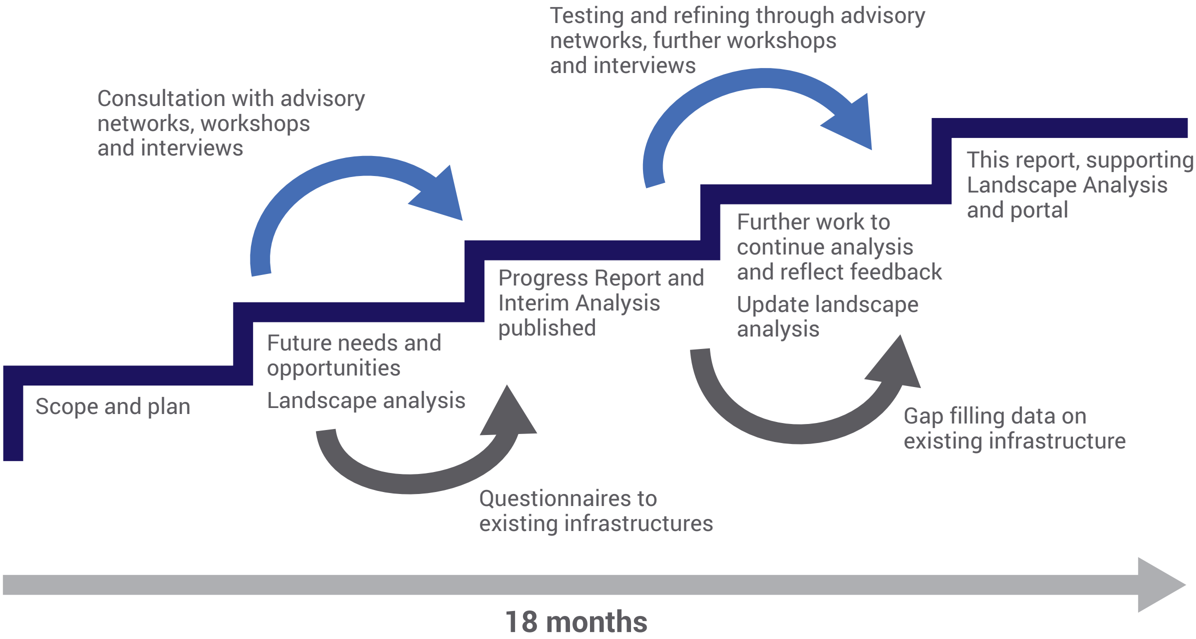


Figure 6. Developing this report.

We have benefitted from substantial support and input from across academia, representative bodies, learned societies, business networks, charitable organisations, universities, PSREs, the Catapult network, government departments, funding bodies, the Devolved Administrations and UK Research and Innovation's extensive network of advisory committees. The programme has also drawn on an Advisory Board, (which includes representatives from UK Research and Innovation Councils, the Department for Business, Energy and Industrial Strategy (BEIS), BEIS-funded PSREs, Universities UK, the Association for Innovation, Research and Technology Organisations (AIRTO), Devolved Funders and the Royal Society. We are also grateful for insights from colleagues responsible for the development of roadmaps in other countries and from ESFRI, and to international representatives who participated in a workshop at the 2019 Annual Meeting of the American Association for the Advancement of Science (AAAS).

2.4 Aim of this report

This report provides an assessment of the future research and innovation infrastructure landscape reflecting the feedback received on our Progress Report and further work to develop options for delivering capability needs. The report is intended as a strategic guide to inform future national and international investment decisions across different priority areas and, given its breadth, does not attempt to explore each issue in detail.

In the context of the goal to reach at least 2.4% of UK GDP invested in R&D, this report is deliberately ambitious and provides an overview of infrastructure opportunities that could lead to a step-change in the capability available to researchers and innovators over the next ten years. However, budgets will always be limited and it is unlikely that we will realise everything described here. This report does not represent a funding commitment or seek to prioritise the funding of particular infrastructures. Ultimately, future funding to develop existing infrastructures

CASE STUDY:
World-leading Antarctic infrastructure has global impact

The UK Antarctic research stations operated by the Natural Environment Research Council (NERC) British Antarctic Survey represent the UK's Antarctic presence in line with the Antarctic Treaty and supports multidisciplinary, cross-sector science, such as, innovation in engineering in extreme environments. They have consistently facilitated excellent science with global impact, including discoveries such as the hole in the ozone layer, plastic microbeads at the poles, and have improved projections of ice sheet change and sea level rise. Maintaining this is vital for research to better understand how the polar regions are changing in light of natural and human-driven pressures, building a clearer picture of how this impacts on our global climate.

From 2020, the UK's new £200 million polar research ship, RRS *Sir David Attenborough*, will support up to sixty scientists on board with state-of-the-art laboratories and equipment, including remote and autonomous underwater vehicles. It is the first UK polar research vessel with a helipad and a scientific moon pool and will operate in both the Arctic and the Antarctic.

British Antarctic Survey

or create new capability set out here will be dependent on strategic investment decisions and availability of funding from a range of organisations including the government and UK Research and Innovation.

The report is focused on the strategic choices and step-changes in capability needed to support the strategic goals and objectives set out in the UK Research and Innovation Delivery Plans[33]. These capability gains can be achieved through provision of new capability, upgrading or evolving existing capability, and consolidation or more effective use of existing capability alongside decommissioning activity where user needs have evolved. We have not explored the maintenance of existing capability in depth; however, this is also a vital part of the infrastructure landscape and the wider ambition to raise the total R&D investment to at least 2.4% of GDP by 2027. The Delivery Plans[33] provide additional context for these investments.

To develop a longer-term perspective on UK infrastructure requirements we have captured both more developed ideas and areas which are considered vital to progress, but where our understanding of what is needed requires further exploration:

- **Stage 1:** Our understanding of the requirement is at an early-stage and detailed follow-on work is needed to develop an understanding of the infrastructure implications. This might take the form of an in-depth roadmapping exercise or community engagement through meetings or strategic calls for expressions of interest
- **Stage 2:** The need for infrastructure is clear but this could be achieved in multiple ways and a strategic options analysis is required to help build a detailed case
- **Stage 3:** The concept for the infrastructure requirement is clear and ready either to progress to implementation or to conduct a pilot, scoping or design study which will refine delivery or technical options and allow for more informed decisions on whether or not to proceed further

This reflects our intention to build a pipeline of ideas and infrastructure requirements for the longer term. This inevitably means some capabilities are more developed than others and we have highlighted where more detailed scoping work would be beneficial to progress from an early-stage idea to a more concrete project. The level of detail provided in each of the following chapters also reflects the nature of the discipline and the way different research and innovation communities work. For instance, some activity is inherently more scalable and can be approached in several ways while in other areas options are more defined. The development cycle also varies substantially across different disciplinary areas, e.g. e-infrastructure development cycles of two to five years compared to the decadal planning cycles of large-scale, multi-sector facilities. A number of infrastructure capabilities also fall into natural groupings which have been indicated within the chapters:

- **Themes and subthemes:** where infrastructure capabilities operate independently but are collectively working towards a common strategic goal and therefore a critical mass of activity can greatly enhance impact
- **Groups of interdependent activity**: where one or more infrastructure capabilities are necessary to achieve subsequent actions, i.e. it is not possible to undertake project C before projects A and B have been successful

It is well understood that many infrastructures work across sectors, rely on common technologies and techniques and face common challenges regardless of their primary focus. Alongside the sector-focused chapters, we describe some of the infrastructure capabilities that are designed to support interdisciplinary and multidisciplinary activity. This includes e-infrastructure as a critical underpinning capability that supports work across the landscape. We also discuss the potential for greater connectivity across the landscape and address some of the cross-cutting needs that will impact on all infrastructure regardless of subject focus, model, operation or user base.

This report is intended to be read as a stand-alone document. However, readers may also refer to the previous Progress Report and latest Landscape Analysis[18], which set out a more in-depth description of the strategic context and current landscape in each sector.

Chapter 3: Biological sciences, health and food sector

Gerd Altmann from Pixabay

Advancing our understanding of living organisms, from microbes to humans, is at the heart of this sector – from their molecular and structural complexity, their connections, adaptations and diseases, to their interactions with the changing environment. Such research drives innovation in agriculture and food production, strengthens our ability to identify and treat illness and ensures the UK can respond to some of the biggest challenges of the twenty-first century. Whether centralised or distributed in nature, infrastructure in this sector supports UK competitiveness in major, globally mobile and rapidly changing industry sectors from pharmaceuticals through to agricultural technology.

The biological and medical sciences are poised for major advances using new technologies which, when integrated and supported with excellent informatics and analytics, can reveal how the myriad of interactions between biological molecules and across cells and tissues combine to make life, and how they can be changed and manipulated to improve health and productivity. These new technologies generate data on much larger scales and over longer time periods than previously possible and often require the use of AI approaches (e.g. machine and deep learning) to unravel this progressively data-rich environment. This combination of 'big data' and AI is enabling the life sciences to link genome and phenome to wider environmental and physical data, opening up possibilities for truly ground-breaking research in areas such as dynamic reconstruction and predictive modelling. At the same time, the sector's infrastructure must study life in the places where it happens – in a forest, on a farm, in a hospital or in the home. This real-world context shapes how our infrastructures are organised and where they are placed.

CASE STUDY:
Boosting innovation: the Medical Research Council (MRC)/AstraZeneca Cambridge Centre for Lead Discovery

AstraZeneca

Access to advanced technology helps to make the process of drug discovery smarter, faster and cheaper. The Centre for Lead Discovery supports collaboration between researchers and industry scientists and access to industry infrastructure to advance discovery research. This collaborative centre supports unprecedented academic access to AstraZeneca's chemically diverse screening library of over 2 million compounds, and access to the world's most advanced 'drug discovery robot' (NiCoLA-B), which performs high-throughput screening via a drug discovery robotics platform.

State-of-the-art robotics and technology allow companies the ability to screen more than 300,000 compounds a day. Providing academic access is helping MRC researchers find new biological targets to accelerate potential therapies from laboratory bench to patient bedside and promotes open innovation.

Research and innovation in the biological sciences, health and food sector is highly collaborative and thrives on mutually beneficial partnerships that are often multidisciplinary in nature. This can involve access to high-tech facilities and bespoke computation and data infrastructures, together with the innovation space that nurtures the next-generation of UK companies. As part of UK Research and Innovation, the Biotechnology and Biological Sciences Research Council (BBSRC) and Medical Research Council (MRC) provide around half of the national public sector investment in life sciences. There are also major contributions from the Department for Environment, Food and Rural Affairs (Defra) and the Department of Health and Social Care including via NIHR and the Devolved Administrations. In this sector, research charities including the Wellcome Trust and the Gatsby Charitable Foundation are major investors and partners in developing infrastructure.

Life science-based industries are among the UK's most important investors in research and innovation, with high R&D investment and major contributions to exports and employment. According to the Office for Life Sciences 2019 report, the life sciences industry employs just under 250,000 people and generates an annual turnover of £74 billion[35]. As well as being important users of infrastructures, industry is key in the co-development of new technologies. Industry-owned infrastructure or data resources are increasingly being shared with academia through the development of partnerships (see case study).

3.1 Overview of current capability

This sector covers all areas of biological and medical science, from plant and agricultural science, to food science, whole-organism phenotyping, biomedical and clinical science and marine science (Figure 7). Infrastructures are key to tackling the research and innovation challenges across the life sciences, whether these are predominantly purposed for this sector or are multidisciplinary. Data from the Landscape Analysis show that most biological sciences, health and food infrastructures (92%) report collaboration with other organisations either nationally or internationally, and the majority provide resources or services to the wider community. Over three quarters of infrastructures in this sector (76%) engage with industry, benefitting a range of sectors of the economy including health services, research and engineering services, agriculture, the food industry and the pharmaceutical industry.

The sector is well linked with important **international infrastructures** and is involved in six of the thirteen health and food infrastructures in ESFRI. These resources include biological data, physical biobank samples, imaging facilities and molecular screening centres, e.g. European Life Science Infrastructure for Biological Information (ELIXIR), Biobanking and Biomolecular Resources Research Infrastructure (BBMRI) and the European research infrastructure for imaging technologies in biological and biomedical sciences (Euro Bioimaging). These infrastructures are increasing efforts to join up across Europe, e.g. through Coordinated Research Infrastructures Building Enduring Life-science Services (CORBEL) and European Open Science Cloud-Life (EOSC-Life).

Networking distributed regional-scale infrastructures into a national capability is a common feature (or an aspiration in emerging or establishing areas) in the sector, such as networks of specialist microscopy facilities (e.g. feeder platforms for optimisation), phenotyping facilities or bioinformatics resources. In some cases, a nationally significant network comprises the UK node of a large-scale international infrastructure partnership such as those supported under ESFRI, demonstrating again that connectivity and partnership is at the heart of the sector.

This sector also uses **large-scale, multi-sector facilities** such as Diamond Light Source (Diamond) (Chapter 9) and is home to a number of internationally important **reference laboratories addressing global challenges**, e.g. The Pirbright Institute hosts the World Reference Laboratory for Foot and Mouth Disease and the Francis Crick Institute hosts one of six World Health Organisation (WHO) Worldwide Influenza Centres responsible for analysing influenza viruses circulating in the human population.

The sector is increasingly dependent on **e-infrastructures**. Specialist computational architectures and configurations are essential for making sense of and managing the vast amounts of data accessible from across the globe. UK-based leadership in managing, integrating and analysing valuable data resources and making them accessible to millions of global users puts us at the forefront of new discoveries and at the centre of a highly competitive world stage. Life science data infrastructures can extend across and beyond the sector – for example, the world-leading European Bioinformatics Institute (EMBL-EBI) at Hinxton; others are targeted towards a specific challenge such as food security (e.g. the Earlham Institute) and human health (e.g. Health Data Research UK).

The Landscape Analysis[18] shows that approximately 70% of all UK infrastructure report some relevance to the life sciences. Of the infrastructures categorised as having a regional, national or international scope, approximately one third reported their primary domain as the biological sciences, health and food sector. Examples range in scale and scope from single pieces of cutting-edge, high-cost equipment (e.g. ultra-high-field Nuclear Magnetic Resonance (NMR) for structural biology) to very long-term human population cohorts, and from networks linking groups of cutting-edge technology (e.g. the 7T Magnetic Resonance Imaging (MRI) network) through to field- and farm-scale platforms which comprise a range of in situ state-of-the-art instrumentation.

Figure 7. Biological sciences, health and food sector diversity and dependencies.

3.2 Future direction

The aspirations in the biological sciences, health and food sector align well with the government's ambitions to lead in high-impact technologies and align with the directions set out in the Life Sciences Industrial Strategy[36] and the Bioeconomy Strategy[37]. This sector also supports the Clean Growth Strategy[38] through helping to develop low-carbon technologies such as the manufacture of bioplastics from waste or using precision agricultural approaches to reduce the use of pesticides and fertilisers.

This sector has a diverse existing portfolio of infrastructure which needs to be **maintained at appropriate levels of performance and capacity and to evolve** as technical advances are made (e.g. speed, resolution and throughput) or as scientific questions necessitate new approaches. **Rigorous, regular reviews** are an essential part of ensuring the current infrastructure remains relevant to the UK's research and innovation landscape. In addition to research needs, the local environment (e.g. health service operational change, or biosecurity) and the need for sustainable productive partnerships around the facility should be fully considered in funding decisions and organisational models. As with all sectors, resources to develop, adopt and uptake **disruptive technologies** alongside investment in the infrastructure itself are a critical part of any transformation in approach.

Technological advances are driving the biological and biomedical sciences to move from a reductionist to a **holistic understanding of the dynamic biological systems** that comprise life. This necessitates looking across scales from the atomic resolution of biological molecules, to single- cells and cell types in large populations, in silico modelling of complex biological systems with high degrees of explanatory and predictive power. The field of multiscale biology, where the boundaries between scientific specialisms are converging into a new, highly multidisciplinary field, is emerging to address this challenge.

The increase in the use of methods that generate very high volumes of data will continue into the next decade, with experimental data coming from:

- High-resolution biological and medical imaging which produces petabytes of data
- High-throughput, high-fidelity genomic sequencing and other 'omics analysis
- Industrial-scale chemical screening
- Automated multiplex assays, alongside the use of miniature 'lab-on-a-chip' platforms

The volume, variety and velocity of life science data generation requires new capacity, people and methods to turn data into knowledge. It is essential to improve the curation of e-data, to record its provenance and to ensure that the full value can be extracted from it over the coming years as more sophisticated methods and models are developed. Creating new translatable knowledge also requires a systems-level understanding. Integrating multiple complex biological data types together with patient data, for example, will aid the identification of the molecular signatures of health and disease and support precision approaches to early diagnosis and the development of novel therapeutics.

Many of the new approaches and scientific challenges to be addressed will require access to **integrated suites of state-of-the-art equipment**, which are best situated in dedicated centres or hubs, with an appropriate ecosystem of support including specialist staff. Networking these centres and hubs at a national (or international) level will give further benefits from economies of scale, and through sharing knowledge, methods and best practice.

As we move forward laboratories will increasingly use high-tech robotics and the automation of routine assays linked to data integration. High-cost, cutting-edge analytical infrastructure for molecular and cell biology (including imaging, 'omics, cell culture and manipulation), will be linked with data networks and new bioinformatics, statistics, computing and software solutions (including machine learning) to allow real-time data-sharing across sites. This **increasingly automated approach** will become pervasive across the life sciences and early adopters are likely to be in high-throughput areas (e.g. genomics and phenotyping). This will engender a change in the dynamics of research work and the research culture.

Mobile technologies, sensors and nanotechnology are also expected to transform life science research and innovation, taking it out of the laboratory and into the hospital or field. Mobile technologies and remote biosensors will allow the creation of large population cohorts in their environmental context that can be monitored remotely over long periods of time. The use of in-field sensors and drones combined with Earth data provides new opportunities for improving agricultural productivity at the farm-level (such as by supporting improved farm-level decisions), as well as understanding the impact of agricultural production from the level of an individual wheat grain to the grain belts of Europe, the USA and beyond.

Increased support for development and application of new life science discoveries and technologies, whether experimental medicine therapies or more resilient and sustainable agricultural practices, are essential to support the health and wealth of the UK population and its economy. De-risking and testing new innovations are a key element of translation and require time, specialist facilities (e.g. clinical research centres, breeding/animal facilities, or farm-platforms) and understanding of regulatory requirements. Developing infrastructures to support translation (e.g. experimental medicine, small-scale manufacturing) and to increase integration of expertise across academic, industrial and clinical research, NIHR and NHS end-users will increase economic benefits.

3.3 Future requirements and opportunities

The pace of progress in biological sciences, health and food research is increasing with the development of ever more sophisticated and powerful technologies and innovations. This creates a challenge in developing and refreshing the UK's biological, biomedical, biophysical, clinical and agri-food research infrastructure and calls for strong partnerships with key stakeholders and national-level public investment to deliver priority infrastructure.

Within each of the following themes we present some important opportunities for future infrastructure capability. These themes have been refined to reflect feedback received on the Progress Report. As described in Chapter 2, these are at different stages of development. Some opportunities need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered, whilst others are more developed and should be implemented sooner.

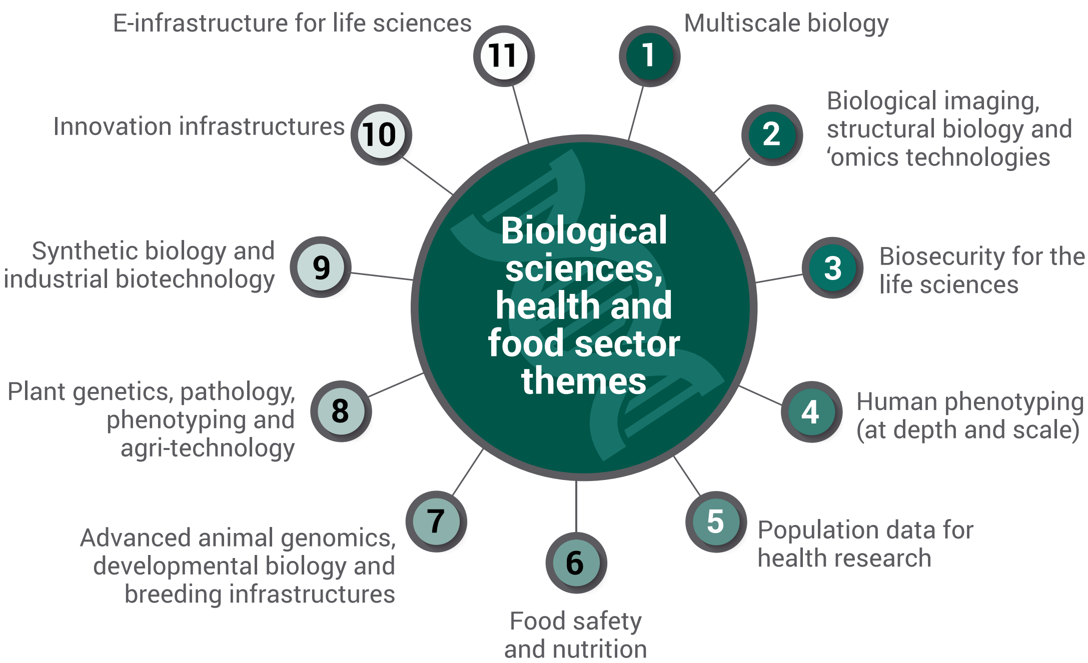


Figure 8. Biological sciences, health and food sector themes overview.

Themes 1 & 2: Multiscale biology, biological imaging, structural biology and ‘omics technologies

Multiscale biology has emerged as an exciting new area, including the convergence of different approaches to empirical life science data-gathering, data integration and mathematical modelling. Complex biological data arising from the latest technological developments in imaging, ‘omics technologies and structural biology across scales from molecules to organisms, and across short and long timescales, will be integrated utilising computational approaches (including machine learning and AI) allowing researchers the ability to be able to ‘zoom in and out’ of molecular, cellular and physiological events and to gain insight into the complex mechanisms behind normal function and disease. This will allow us to move to a more dynamic understanding of the interplay between biological pathways, networks, spatial organisation and environment against time and to gain deeper understanding of biological function and how it is compromised by damage from environmental challenges or disease (see case study).

CASE STUDY:
Single-cell technologies

The National Capability in Genomics and Single-Cell Analysis provides scalable infrastructure for high-throughput DNA analysis of biological systems from ecosystems to individual cells. Embedded in the Earlham Institute’s data-intensive research environment and backed by one of the largest High-Performance Computing systems dedicated to bioscience in Europe, this capability is uniquely positioned to deliver the tools, resources and services needed to tackle global issues through genome science.

The newly established single-cell analysis facility extends the remit from organisms to individual cells at a resolution not possible before. It supports research in plants, microbes and animals, with a particular focus on agricultural science and bioscience for health. It also plays a key role in bio-surveillance by providing rapid genomic analysis of plant pathogens during outbreaks, such as ash dieback.

Pioneering single-cell technologies are also used to improve the diagnosis, stratification and treatment of human diseases; in parallel, MRC’s Clinical Research Infrastructure Initiative funded a family of seven smaller-scale resources in biomedical centres from Exeter to Newcastle. For example, the Oxford Single-Cell Consortium has access to robotics and ultra-clean environments to perform single-cell experiments. New computational and statistical methods are used in areas such as stem cell transplantation, mechanisms in inflammatory bowel disease and ageing, at the level of the single-cell. The consortium works with the other centres across the UK on new techniques and analytical methods.

Earlham Institute

Multiscale biology needs a distributed national infrastructure which, as illustrated in Figure 9, enables convergence of **structural biology** (e.g. X-ray diffraction and electron microscopy), **imaging** (e.g. optical, photoacoustic, lasers, electron tomography and correlative approaches) and **multi-'omics** (e.g. proteomics, metabolomics, transcriptomics and genomics) coupled with **high-throughput automation** across scales. Managing the high-dimensional data outputs will require the development of increasingly sophisticated **data integration and modelling methods**.

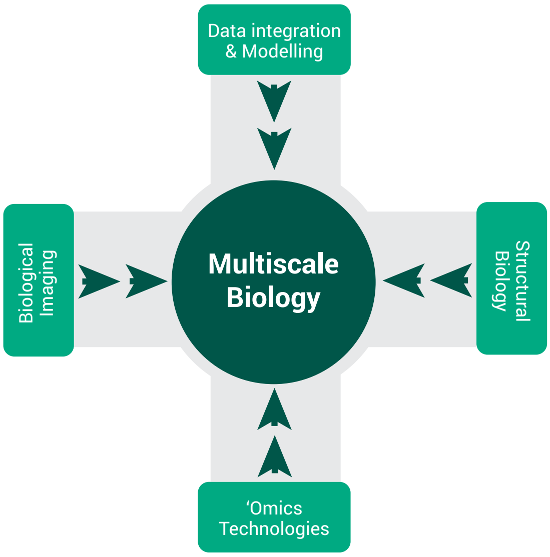


Figure 9. Multiscale biology enabled by the convergence of imaging, 'omics technologies, structural biology and data analytics.

Alongside the longer-term ambition of multiscale biology, there is the parallel need for new biophysical and imaging technologies. Understanding how molecules function and interact will be invaluable for broader advancements such as in: novel drug discovery; understanding host-pathogen interactions in plants, animals and humans; and combatting Antimicrobial Resistance (AMR). The equipment and technologies required sit on a spectrum from those which reside in well-found labs at a local level through to those which need to be housed in specialist regional or national centres, with appropriate support systems, such as the Rosalind Franklin Institute or the electron Bio-Imaging Centre (eBIC).

Biological and biomedical imaging: Bioimaging research needs a diversity of specialist imaging modalities including techniques that allow the study of sub-cellular processes, and intravital imaging which allows the study of processes in living tissues (e.g. 3D cultures of cells including organoids) and animals, to non-destructive imaging of whole organisms using X-ray Computed Tomography (CT) technology for high-resolution 3D images of internal structures (e.g. of plant roots in situ). The power of research tools is steadily increasing with major advances such as super-resolution microscopy, which can break the light diffraction barrier at the 10-20nm level, and atomic force microscopy, which can measure the mechanical properties of a sample at high resolution to obtain images at the molecular scale in living samples. The highest resolution is obtained by Electron Microscopy (cryo-EM) – a technique that provides detail at near-atomic resolution.

Structural biology: The UK is a world leader in structural biology with the MRC Laboratory for Molecular Biology (MRC LMB) winning seven Nobel Prizes. The UK houses world-leading facilities that bring together the leading generation of biophysical technologies for structural biology and contribute to its international reputation (e.g. MRC LMB, Central Laser Facility), including key techniques such as crystallography, NMR, cryo-EM and mass spectrometry and spectroscopy. The requirement for improved mass spectrometry is driven by complexity, but also by the need to analyse small samples (e.g. micro-dissected tissue and organoids) and the progressive drive to be able to analyse single-cells using mass spectrometry.

'Omics technologies: While some areas are well established with highly specified technologies, such as gene sequencing, other 'omic approaches are less well served and require new technological advances to improve detection and isolation (e.g. metabolomics). The increasing need to analyse highly complex biological samples requires new methods with improved detection, better identification and more accurate quantification of larger numbers of metabolites. Proteomics has expanded rapidly, aided by improvements in instrumentation, accuracy and sensitivity in identification and quantification of the thousands of proteins in a biological sample. These findings support the analysis of cellular signalling networks and elucidation of the dynamics of protein interactions, and provide insights into the biochemical state of the relevant cell or tissue. A common challenge is the assimilation and interrogation of terabytes of information to reveal detailed phenotypic and functional readouts of cells, tissues and organisms. This requires new software solutions and methodologies (including new AI tools) and the ability to integrate data across imaging platforms for new correlative analysis and linkage to other data sets (e.g. across imaging scales and with transcriptomic data, e.g. in the Human Cell Atlas) to deliver a systems-level understanding.

The technologies, analytics and mathematical modelling require close working with the physical and engineering, medical and environmental sciences. UK facilities are valued by industry as hubs of technology development, training and expertise and have supported the commercialisation of technologies which are now used worldwide.

Theme 1: Multiscale biology

The ambition is to create UK-wide multidisciplinary capability spanning biological scales across human, animal and plant research, to illuminate biology in action and put the UK at the leading edge of this emerging field. This infrastructure will revolutionise our ability to view the complex mechanisms and interplay of intricate structures that make life happen and integrate layers of multimodal data to understand currently intractable problems.

How this area can be progressed/indicative approaches

Multiscale biology centres and hubs	A national network of highly specialised centres of excellence would bring together a broad range of cutting-edge analytical technologies with robotics, automation and data analysis and support systems. These new 'labs of the future' would deliver quantitative analysis and scale-up for integrative and dynamic biology across molecules, cells and tissues in plants, animals and humans. They may focus on: ■ Biological challenges, e.g. biological systems, human/plant/animal disease ■ Technological challenges, e.g. working at the boundaries of their technologies or expertise and pushing methods development around data integration in that area The centres would also support some of the development of computational models and correlative analysis (e.g. modelling and simulation at appropriate levels of abstraction).
National integrative analytics platform	Cross-disciplinary platforms would enable comparative analyses across the hubs and smaller research programmes, including computational models, correlative analyses, development of innovative algorithms and software such as AI, data management and data standards. This would require access to data-intensive hardware (e.g. High-Performance Computing (HPC) or High-Throughput Computing (HTC)), software for processing and analytics and data storage (such as hybrid storage solutions allowing local processing and longer-term storage).

Theme 2: Biological imaging, structural biology and ‘omics technologies

Biological imaging, structural biology and ‘omics technologies are key to the multiscale approach but retain their own research directions and discrete infrastructure requirements. At the boundaries of each of these, there is an intersection of approaches leading to some shared infrastructure needs. Access to the latest technologies is key for all researchers, but the specialist nature can require them to be provided via a hub with appropriate support structures. New specialised facilities are needed to establish platforms for innovation and to enable the UK community to participate in large international programmes.

How this area can be progressed/indicative approaches

Networks of specialised centres for advanced imaging, structural biology and ‘omics technologies

Specialist centres would offer a distinctive package of leading technologies, supported by local ‘feeder’ instruments and sample preparation capabilities, collectively brought together into a national network. These centres would also have an important role in developing new technologies (often in partnership with industry) and then making them more widely available. This would provide access to world-leading expertise and approaches, e.g. optimisation stations and correlative methods. For example:

Biological imaging technologies:

- High-voltage transmission and scanning cryo-EM to reveal the atomic structure of biomolecules
- Super-resolution microscopes that break the light diffraction barrier to reveal the properties and dynamics of cells and tissues (e.g. photoactivated localisation microscopy, stochastic optical resolution microscopy, stimulated-emission depletion microscopy, 3D structured illumination microscopy, total internal reflection fluorescence microscopy and light sheet fluorescence microscopy)
- Tomography: optical coherence tomography, optical projection tomography, micro X-ray CT and magnetic resonance to reveal the underlying architecture of plants, animals or humans
- Atomic force microscopy

Structural biology technologies:

- X-ray crystallography and protein production
- NMR
- Optical and electron microscopy
- Biophysical technologies: absorption spectrophotometry, circular dichroism, ionisation techniques and isothermal titration calorimetry
- Cellular EM Tomography
- Mass spectroscopy, spectrometry

Multi ‘omics technologies (proteomics, metabolomics, transcriptomics, epi/genomics and other ‘omics approaches)**:**

- Functional genomics, next-generation sequencing and platforms, expression profiling technologies, whole exome and genome sequencing, High-Throughput Ribonucleic Acid (RNA) expression profiling
- Mass spectrometry for analyte detection, ionisation technologies, e.g. surface-enhanced laser desorption/ionisation, quantitative electrophoresis, and chromatography
- Spectroscopy for metabolite detection

Image repositories and novel data platforms	Novel data platforms, image repositories and 'omics data integration: at sufficient scale would support the storage, transfer, manipulation and interoperability of large data files and collections, and provision for open access.
UK partnership in current and future international infrastructures	National networking as preparation for any UK node(s) as part of international coordination activities, or membership of relevant international consortia, e.g. ESFRI, Euro-BioImaging and Global BioImaging projects and Instruct-ERIC for structural biology. This would facilitate sharing of specialist infrastructure, collaboration opportunities, training facilities and agreed protocols for data-sharing and access.

Theme 3: Biosecurity for the life sciences

Zoonotic diseases (including vector-borne diseases), resistance to antimicrobial compounds and infectious disease risks to human, animal and plant health are substantial challenges facing the UK[39]. They cause significant economic losses (e.g. swine flu, foot-and-mouth disease virus), affect food security and pose a serious threat to health across the globe (e.g. AMR to colistin). Over 900 pests and pathogens currently pose a threat to the UK's arable crops, trees, horticulture and wild plants, and zoonoses represent at least 75% of emerging infectious diseases in humans. Specialist infrastructures form an essential part of the UK's preparedness in the event of disease outbreak or other attack by helping prevent, control, treat and eradicate major human, animal and plant diseases. An integrated whole-system approach will be necessary and requires diverse infrastructure including national basic research and reference laboratories, diagnostic facilities, biosafety level 3 (BSL-3)/category 3 (CAT3) or higher containment facilities, infrastructure for surveillance, and detection and prediction of animal and plant health risks (e.g. the UK Animal and Plant Health Internet of Things and the CropMonitor Pro service from the Crop Health and Protection (CHAP) Agri-Tech Centre).

The requirement for appropriate surveillance, outbreak monitoring and analysis and contingency preparedness plans has been demonstrated by the recent Ebola virus outbreak in West Africa, which killed large numbers of people and cost external partners around £2.7 billion to support the world's poorest communities in containing the outbreak. The UK is implementing the £4.85 million BRIGIT programme to improve detection and prevent the spread of the insect-transmitted bacterial plant pathogen Xylella, which infects 500 species of crops, trees and ornamental plants and has had devastating effects across Europe after transmission from the Americas (e.g. killing over 1 million olive trees in Italy). In addition, there is a need for facilities to foster and translate technology developments into application, e.g. new vector control methods, infection prevention and control approaches, vaccine development and manufacture, and sensor and mobile device development.

An integrated approach is required to tackle these biosecurity challenges. This would bring together fundamental biological and biomedical knowledge with knowledge from animal, plant, pathogen and vector genomics, phenotyping, epidemiological data and environmental data (e.g. climate modelling).

Theme 3: Biosecurity for the life sciences

The UK needs world-leading infrastructure to combat zoonotic diseases (including vector-borne diseases), resistance to antimicrobial compounds and infectious disease risks to health (human, animal and plant) globally.

Internationally important infrastructures enable research to prevent, control and eradicate major diseases; and to protect human health, livestock and crops: and are vital to the UK's preparedness in the event of disease outbreak or other attack.

How this area can be progressed/indicative approaches

The Pirbright Institute	The Pirbright Institute is a critical national capability for biosecurity research and surveillance of livestock and zoonotic diseases. It has global leadership in these areas and is the World Reference Laboratory for Foot and Mouth Disease. Upgrading facilities at the institute would enhance capability and research into important viral and vector-borne diseases including: ■ Human pathogens (e.g. Zika, Dengue, Ebola) ■ Transmission of diseases into new regions (e.g. blue tongue virus and lumpy skin disease virus into Europe) ■ New disease threats (e.g. Schmallenberg virus for sheep) These new capabilities could include high-containment laboratories and additional infrastructures, including insectary facilities, and could look to exploit synergies with other government surveillance and diagnostic capabilities for animal disease, e.g. Defra's Animal and Plant Health Agency at Weybridge.
High-containment and surveillance facilities	Investment in capabilities at key national centres would enhance expertise in research using prions or human pathogens not contained by vaccination or resistant to treatment (such as Mycobacterium tuberculosis, HIV and Plasmodium falciparum, vivax (malaria)). These may comprise upgrades to existing, or new high-containment and surveillance facilities including national and world reference laboratories (particularly BSL-3/CAT3 or higher containment levels).
Facilities for diagnostics and vaccine production *(also coordinated with government health departments, Defra and the Animal Health and Veterinary Laboratories Agency)*	Infrastructure is needed to support development of novel diagnostics, new vaccination technologies (e.g. viral vectors, nucleic acid-based vaccines and RNA vaccines) and production systems (e.g. production of virus-like particles as vaccines against Zika virus by Leaf Expression Systems). This would create a new pipeline to fight highly pathogenic viruses, resistant pathogens and other dangerous animal and human pathogens.
Critical national surveillance, modelling, analysis and preparedness *(also coordinated with government departments)*	Networked data infrastructure would bring together information from surveillance systems, epidemiological analyses and health analytics with modelling of infectious diseases. A national infrastructure for monitoring and measuring plant, animal or human pathogens ('Internet of Things' approach) using mobile measuring devices and sensors, e.g. in fields, hospitals or surgeries, would support the UK's preparedness, mitigation, and response plans against infectious disease threats, in a global context.

Themes 4 and 5: Human phenotyping (at depth and scale) and population data for health research

Advances in multiscale biology and related disciplines (imaging, 'omics and structural biology) hold great promise for biomedical and clinical science to explore the spectrum of 'wellness to illness'. Developing detailed multidimensional disease maps (from atomic resolution to organ systems) will transform the use of in silico approaches to understand human biology, disease states and opportunities for diagnosis, intervention and drug design.

The phenotyping of large groups of people (ranging from hundreds of patients to millions of volunteers in population studies) will be needed in order to decipher the genetic basis of biology and disease to robustly analyse disease and pre-disease states, and evaluate diagnostics and treatments for precision medicine. Next-generation sequencing, proteomics and metabolomics data will provide granular phenotypic resolution for 'deep phenotyping' and use sophisticated algorithms to integrate phenotype data with genomic variation. Whereas 'broad' phenotyping at the population scale will shed light on disease heterogeneity and variable response to treatment. Biomedical imaging technologies will support both the study of fundamental questions around disease processes at sub-cellular levels and the development of clinical tools for diagnosis and patient care. Other new technologies offer better information (e.g. functional Magnetic Resonance Imaging (fMRI) to detect and map neural activity in the brain) with higher resolution or over a shorter time and allow new approaches to progress to clinical uses (e.g. using fMRI to differentiate sub-classes of neuropsychiatric disorders or to guide surgical procedures).

UK Biobank was launched in 2006 and is one of the most important resources for population health in the world. This vast infrastructure contains genomic and biomedical data from half a million individuals in the UK who have been followed for ten years. In March 2019, UK Biobank released new genetic data, containing exome sequence data of 50,000 participants linked to detailed health and biomedical imaging data. This will allow researchers developing new treatments to understand genetic differences across the population and how these might impact on treatment success. Over 750 institutions around the world have published studies on a wide variety of diseases and public health issues using UK Biobank data. The NHS is now developing a Genomic Medicines Service, which builds on the recently completed 100,000 Genomes Project; in time this will enable research and implementation to support quicker diagnoses for rare diseases, more personalised treatment and interventions, and improvements to cancer survival through earlier diagnoses and more effective use of therapies.

The UK is internationally renowned for population-based health research and unique cohort studies have been supported for over a hundred years. The world's longest-studied birth cohort, the MRC National Survey of Health and Development, turned seventy-three this year. By following this population from birth, important correlations have been identified, e.g. the heaviest babies were most at risk of breast cancer, children born into lower social classes were more likely to gain weight as adults and women with a higher IQ reached menopause later in life. As the cohort has aged, technology has advanced and imaging technology has been used to scan the hearts, bones and brains of participants and DNA samples have been taken, making this cohort even more valuable.

Exploiting historical, current and future population-based data will require convergent approaches across the bio/social and health field. As NHS data will remain inside the NHS, it will be essential to develop routes to support the analysis and linkage of complex health data. The ability to create links across social, economic and other routine administrative data is key to understanding public health issues, as is ensuring that the public retain trust in research through joint dialogue, understanding consent and the safeguards around the bona fide use of data. A broad strategy should support the assembly, analysis, curation and linkage of cohorts and other data sources, as well as embrace new approaches to data-gathering for large-scale population studies. This should develop more economic methods for the design and analysis of population cohorts, including taking advantage of the convergence of mobile technologies, wearable sensors and sensitive technologies for measuring biological samples. This will enable more individualised lifestyle and decision-making to be possible within the population, and consideration of the health, social and economic benefits.

The MRC strategic review of cohorts[40] highlighted the paucity of studies with large-scale, deep phenotyping data and a limited number of studies that provided a detailed focus on the 'transition to adulthood'. Access to a broad, deeply phenotyped, frequently sampled, large population-based cohort would provide a competitive advantage to the UK in driving precision medicine, AI approaches and digital pathology. Similarly, a timely focus on the transition to adulthood would also reveal insights and impacts on the lives of children who are growing up in the 'age of austerity' and through the social media revolution.

CASE STUDY:
Working with the NHS to accelerate translational research

The NIHR BioResource is a network of over 130,000 volunteers who have agreed to take part in health research. Patients with common and rare diseases and volunteers from the general public are asked to take part based on their genotype and/or phenotype. This allows the BioResource to build cohorts in selected disease areas and help recruit patients to clinical studies with the support of the NIHR Clinical Research Network.

Inflammatory Bowel Disease (IBD) is one disease area where having access to human samples and volunteers is pushing our understanding of a multifaceted and debilitating condition. IBD is a complex condition with many subtypes of disease (endotypes) resulting from a range of biologically distinct disease processes. Currently IBD is not curable (except through radical surgery). The IBD BioResource established in 2016 interfaces across the MRC and NIHR to provide access to patient samples to accelerate the clinical translation of genetics research in Crohn's disease and Ulcerative Colitis (collectively IBD). So far 23,000 patients have provided samples which researchers use in genetic analysis studies, e.g. looking at the effect of genetic variants that increase susceptibility to Crohn's disease.

A smaller group of 1000 newly diagnosed patients is currently being recruited to provide a more detailed set of samples for 'deep phenotyping'. This cohort will offer greater insights into disease mechanisms by undertaking transcriptomic, meta-genomic, metabolomic and proteomic studies. This will allow researchers to hunt for the molecular signatures of disease. These signatures may form the basis of new clinical studies to validate findings and test potential therapies. Ideally this will lead to new therapeutics and drugs to manage or cure this debilitating condition.

Theme 4: Human phenotyping (at depth and scale)

Developing the UK's biomedical and clinical research infrastructure to analyse human phenotypes with high precision and at scale, with consistent technology and data integration across sites, greater lab automation and advanced analytics and AI approaches.

How this area can be progressed/indicative approaches

Clinical phenotyping hubs (technology-led) *For academic, industry and health users, coordinated with government health departments*	Supporting industry, academic and NHS programmes and cooperation with coordinated phenotyping hubs, including primary data-gathering at scale and utilising bespoke and unique facilities, would deliver efficient services across multiple projects and clinical areas building on £170 million of investment in clinical infrastructure made in 2015. Hubs would provide a balance of: ■ Standard core facilities (next-generation sequencing, proteomics and metabolomics data) on at least eight clinical research campuses to enable phenotyping at scale and to support fast recruitment to complex studies ■ Specialist facilities: a broad range of leading capabilities (e.g. biomedical imaging – MRI, Positron Emission Tomography (PET), CT; multi-'omics; wearables and home systems for 24/7 monitoring; robot sample handling and banking; physiological monitoring) which can be used in conjunction with the core facilities ■ Integration facilities working with data outputs from standard and specialist facilities to support data integration and mathematical modelling and linkage through consistent data systems and standards, with standard user access and agreements
Network of flagship centres (challenge-led) *Coordinated with government health departments*	State-of-the-art technology would support research into fundamental challenge areas, e.g. disease or system-based. Provision of specialist facilities could explore areas such as: ■ Multimodal neuroscience and cognitive studies for medical and normal function research, e.g. for brain repair and rehabilitation, or mental health research – exploiting MRI, PET with electrophysiological data and other modalities ■ Development of novel technologies, e.g. high-field (11–14T) MRI to develop advanced diagnostic imaging capabilities

Theme 5: Population data for health research	
Providing new, modern population cohorts to address major knowledge gaps – embracing advances in technology and data linkage to achieve world-class longitudinal studies with richer data, more efficiently.	
How this area can be progressed/indicative approaches	
Population cohort for accelerated disease detection *For academic, industry, health, public and social health users, coordinated with government health departments*	Establishing the Accelerating Detection of Disease programme, a globally unique cohort of up to 5 million volunteers (approximately 1 million surveyed annually) with biomedical samples and analyses would allow research, development and evaluation of methods for detection of earlier disease stages and prevention/early intervention. A broad, deeply phenotyped, frequently sampled, large population-based cohort would drive precision medicine, development of AI approaches and digital pathology. Access to a large data set could increase the sensitivity of the detection of nascent and subtle alterations in molecular markers or morphology, helping to identify the early predictors of diseases and inform potential treatments for the 6,000–8,000 rare diseases that affect a few hundred people worldwide. Scoping work would inform any decision on next steps.
Adolescent cohort *For academic, health, public and social health users, coordinated with government health departments and education departments*	The transition to adulthood is a key life phase. A national-level, longitudinal cohort focused on adolescence would address a key gap in coverage in the UK's available cohort studies. It would support fundamental medical, psychological and social research addressing key stages of personal, physiological and neurological development with major impacts for mental health, physical health, nutrition, obesity and later life choices. Scoping and piloting of potential approaches would inform any decision on next steps.
National platforms for population studies *Coordinated with ESRC and government health departments*	A national-level strategy is required to determine the most appropriate infrastructure(s) to: ■ Preserve and support the UK's unique population cohort data assets, providing a dynamic interface to create standards, data curation, data linkage and interoperability across the bio/health/social space ■ Provide data platforms: Specialist platforms to respond to the challenge of linking and analysing the exponentially increased volume of population-scale, multimodal data, e.g. phenotypes, images, whole genome sequencing, microbiome, diet and activity, and health outcomes data ■ Provide specialist, interconnected platforms to support integration, curation and linkage of broader economic, environmental and social data and policy development ■ Develop digital approaches for new cohorts supporting the economic design, set-up, implementation and long-term maintenance of cohorts
Health Data Research UK (HDR-UK) *Coordinated with government health departments and NHS*	Developing approaches for new areas of data linkage, capture and integration (environmental, lifestyle and more complex biological data) would build on the completion of the Digital Innovation Hub partnership with the NHS.

Theme 6: Food safety and nutrition

By 2050 the world's population is predicted to expand to over 9 billion, requiring 60% more food and a reduction in food waste. The UK is also facing major challenges around food safety and nutrition, from producing safe, sustainably produced, traceable and nutritious food and animal feed to preventing diseases related to malnutrition and food contamination. Food-related ill health alone costs the UK health service £6 billion per year[41]. Future research capability will need to consider the growing need for diets to change in the coming decades and the social and global context, population factors and public health implications of this.

Two key areas need to be addressed:

- **Food systems and technology** – e.g. product development, manufacturing and processing; food safety and provenance; and animal feed (and alternative protein sources for animal feed such as insects), including for livestock and aquaculture
- **Food, nutrition and health** – e.g. the nutritional composition and bio-accessibility of food; the impacts of poor/malnutrition on human health; and the social and biological determinants of food consumption behaviour and how they influence long-term health (including underpinning policy)

A 'food systems' approach brings together aspects of both areas to deliver the 2015 Cross-council vision for Food, Nutrition and Health research[42] and the MRC/NIHR Review of Nutrition and Health commissioned by The Office for Strategic Coordination of Health Research. This approach can be used to develop evidence-based strategies to maximise the positive impacts of food on health – from early life to increasing a healthy lifespan in old age and decreasing the economic and societal costs of chronic or microbial diseases.

Global nutrition considerations are also required to transform health and wellbeing across the world. Nutrition plays a pivotal role in non-communicable diseases in lower- and middle- income countries and also has an impact on response and resilience to infectious diseases. Work continues across UK Research and Innovation, the Department for International Development and the Department of Health, through the Global Challenges Research Fund, to support some of these global challenges.

Theme 6: Food safety and nutrition

Integrating of multidisciplinary bioscience, medical knowledge and population approaches to develop new understanding around food systems technology and food, nutrition and health. Co-locating key capabilities will drive a holistic 'food systems' approach to food safety and nutrition.

How this area can be progressed/indicative approaches

Specialist capabilities for food systems research *Coordinated with partners including health departments, Public Health England, ESRC, the Food Standards Agency*	Investment in key institutes and/or substantial upgrade of existing facilities would create clusters of state-of-the-art technologies, building on expertise across existing facilities, e.g. those provided by the Quadram Institute, the Rowett Institute, Campden BRI and Leatherhead Food Research. This infrastructure would focus on the following research areas: **Food systems and technology** ■ Food innovation and quality: food composition, future foods, personalised nutrition ■ Food safety: reducing microbial pathogens in the food chain, biofilms, AMR; food provenance **Food, nutrition and health** ■ The microbiome, IBD, liver and lipid disease, ageing ■ Population health, societal impact and public health This would underpin the use of technologies such as bioinformatics, imaging, 'omics, nanotechnology and photonics to advance our understanding of food systems and the food safety and nutrition pipeline. It could include collaboration or access to industry capabilities and campuses for food systems research (e.g. Syngenta's Jealott's Hill).

Theme 7: Advanced animal genomics, developmental biology and breeding infrastructures

Advanced genetic and genomic approaches enable scientists to probe the function of, and alter, the genes of animal species. This has major implications for the use of animals in research, their role as models for human health and development, and also in breeding programmes as livestock and food sources.

Advanced animal genomics for biomedical research requires integrated facilities for commonly used species, combining genome editing and breeding technologies with harmonised phenotyping instruments and standards. Discovery research models remain a key tool for understanding the biological underpinnings of health and disease and some expansion of pre-clinical models will be required for precision medicine initiatives. Maximising the knowledge gained from animal models, and relevance, will often need facilities with more advanced non-invasive and intravital imaging, more refined sensors, or 24/7 automated monitoring.

Farmed animal production faces a number of challenges through the impact of climate change on animals and agricultural production systems, the impact of the livestock themselves on the environment, increasing scarcity of natural resources and feed, animal welfare, AMR and genetic diversity. New tools and approaches (e.g. agri-tech precision agriculture), in combination with the necessary breeding infrastructure, will allow the UK to tackle increasing demand for sustainable production of healthy livestock. 'Genome-to-phenome' predictive breeding capabilities for animals (and plants) will transform our ability to connect genotype to phenotype in real farm environments, driving a step-change in both research and its effective translation to enable evidence-based decision-making by farmers and breeders.

As these are global challenges, UK participation in international consortia, such as Functional Annotation of Animal Genomes (FAANG) and the International Research Consortium on Animal Health (STAR-IDAZ), is important to provide UK researchers and innovators with access to international facilities and databases, and with opportunities for collaboration and coordination at an international scale.

Theme 7: Advanced animal genomics, developmental biology and breeding infrastructures

Advanced genomic approaches have the potential to revolutionise animal models of human disease and approaches to livestock breeding. Developing a dispersed ecosystem of world-leading national capability will support approaches to improve productivity, sustainability resilience and welfare, and will support the use of animals and the reuse of animal data to inform the health and welfare of humans while addressing changing consumer demands.

How this area can be progressed/indicative approaches

Research facilities for large or farmed animals	Development of research facilities would enable accommodation of: ■ Farmed species and larger animals including livestock and aquaculture for improved productivity and disease resistance, e.g. the Centre for Innovation Excellence in Livestock, The Pirbright Institute, the National Avian Research Facility ■ Genomics/sequencing infrastructure and phenotyping platforms for genome-to-phenome predictive breeding ■ Infrastructure and tools for precision livestock farming, e.g. real-time monitoring systems ■ The generation of breeding lines, e.g. Scotland's Rural College ■ Pre-clinical access to large animals to develop and test novel therapies, biomedical devices or surgical innovations, e.g. the Large Animal Research and Imaging Facility
Integrated specialist facilities for animal models used in research	Investment in specialist integrated facilities would provide capability for: ■ Genome editing with harmonised phenotyping instruments and standards ■ Insectaries for studies on arthropod vectors and control of pests ■ A national resource for the sharing and reuse of samples, archives and data to support implementation of the 3Rs (replacement, reduction, refinement) and research reproducibility ■ Translation facilities, e.g. developing and producing vaccines

Theme 8: Plant genetics, pathology, phenotyping and agri-technology

Understanding the molecular basis of plant life is essential not only to enable the UK to maximise crop yields and support sustainable production but also to underpin development of a wide range of new products and processes of economic and societal benefit. For example, novel therapeutics and antibiotics, metabolic engineering and development of vaccines, foods with improved nutrient contents, industrial feedstocks and catalysts and environmentally-friendly agrichemicals. Due to the relative ease of manipulation, plants are also used as model systems to understand aspects of fundamental biological functions. Infrastructure investment can build our understanding of the molecular basis of plant life and how this can translate to, for example, new breeding lines and technologies for the agricultural industry, as outlined in the UK Strategy for Agricultural Technologies[43].

This requires coordinated (and often co-located) investment in infrastructure including specialist molecular biology laboratory facilities (with appropriate containment where needed), high-throughput and specialist sequencing technologies, plant transformation facilities, controlled environment growth rooms, glasshouse facilities and field-scale trial sites.

Germplasm development in major crops is pre-competitive and public sector investment will be key to furthering predictive breeding approaches, providing markers and developing phenotyping tools and technologies for breeders (e.g. the Designing Future Wheat programme[44]). Precision agriculture, which aims to optimise returns on inputs while preserving resources, will require a variety of equipment and capabilities to function across scales and crop types, complementing programmes such as the Industrial Strategy Challenge Fund (ISCF) Transforming Food Production programme. Developments in this area are particularly important as they underpin sustainable agriculture.

Multiscale phenotyping facilities will be crucial, including advances in robotics technologies as well as large-scale field infrastructure and unmanned aerial vehicles (UAVs) delivering 'lean' field phenotyping, where portability of phenotyping equipment is maximised. Technology developments across agriculture, including in precision agriculture, phenotyping and AI (e.g. to improve farm-level decision-making), will require translation through means such as the Agri-Tech Centres (CHAP, Agri-EPI, Agrimetrics, and the Centre for Innovation Excellence in Livestock) for use by farmers, breeders, growers and industry.

Theme 8: Plant genetics, pathology, phenotyping and agri-technology

Advancing the understanding of the molecular basis of plant life will enhance health, quality and yields for UK and worldwide benefit. Integrated infrastructure is required comprising equipment and capabilities for plant genetics, genomics, pathology and phenotyping, and developments in infrastructure and technology for translation into the agri-tech sector. This will be essential for the UK to 'bridge the genotype-to-phenotype gap' to maximise yields towards food security and support sustainable crop production in times of a changing climate.

How this area can be progressed/indicative approaches

Centres of excellence	State-of-the-art specialist facilities would enable the multi-faceted and multidisciplinary integration needed to address these challenges. This would include dedicated specialist laboratories and technology platforms, controlled environment and in-field facilities and capacity for storage of plant genetic materials. An example would be investment into next-generation infrastructure at the John Innes Centre/ Sainsbury Laboratory to create a national hub for plant and microbial research developing critical mass and important complementarity from co-location with other key institutes on the Norwich Research Park. Major upgrades to existing facilities at other key UK institutes, such as Rothamsted Research, the Institute of Biology, Environmental and Rural Sciences, the National Institute of Agricultural Botany, CHAP, Agri-EPI, Agrimetrics and university-based large facilities, would enable the UK to keep abreast of the significant technological developments being made in this field, e.g. in breeding technologies, precision agriculture and phenotyping.
Large-scale phenotyping facilities, field-scale systems and farm platforms	Investment in large-scale phenotyping facilities, field-scale systems and farm platforms will be key to advancing plant science and agriculture. Bringing these data together with multiscale biology approaches will engender new knowledge and add value to these infrastructures. Priority areas would include: ■ Precision agriculture (e.g. high-tech combine harvesters, remote-sensing systems) ■ 'Lean' field phenotyping (e.g. UAVs for field-scale imaging, handheld devices for pathogen detection or portable crop- monitoring systems) ■ In-field robotics technologies ■ In-situ state-of-the-art instrumentation for monitoring field or farm-scale inputs and outputs
Development of a UK network/node for plant and crop phenotyping	Coordination of plant and crop phenotyping facilities to build a networked national capability, which could function as the UK partner in international programmes (e.g. a UK node for the European Infrastructure for Multi-Scale Plant Phenomics and Simulation (EMPHASIS) programme).

Themes 9 and 10: Synthetic biology and Industrial biotechnology, and Innovative infrastructures

Delivering the Life Sciences Industrial Strategy[36] and increasing inward investment from the bioscience sector requires investment in infrastructure for discovery science to translate new knowledge to market.

Synthetic biology and industrial biotechnology have the potential to deliver new products, applications and industrial processes through the (re)design and engineering of biologically based parts and systems and the use of cell factories and enzymes for producing and processing materials and chemicals. Developments through the use of synthetic biology approaches have the potential to support both fundamental discovery research and also a range of application areas. Industrial biotechnology is strongly supported by synthetic biology, through the provision of tools and technologies such as metabolic engineering, seamless genome modification and enzyme repurposing. Synthetic biology and industrial biotechnology are essential to establishing a sustainable bioeconomy, moving away from the fossil fuel-based economy, as envisaged in the government's Bioeconomy Strategy 2018–2030[37] and Clean Growth Strategy[45]. This requires multidisciplinary, specialist centres with state-of-the-art integrated laboratory facilities which offer high-throughput and automated approaches, underpinned by powerful computing capabilities for AI, modelling and simulation.

CASE STUDY:
The Open Access Biorefining Centres; R&D innovation across the UK

The BEACON Biorefining Centre, Biorenewables Development Centre (BDC), Centre for Process Innovation (CPI) and Industrial Biotechnology Innovation Centre (IBioIC) provide services that help support growth in the bioeconomy. The Centres accelerate and de-risk commercialisation of bio-based product manufacturing and biorefining technology development. This includes development and scale-up of sustainable processes and products from plants, algae and waste streams:

CPI

- BDC, working with the Centre for Novel Agricultural Products, has established two pilot pre-industrial seaweed biorefinery plants which are being used to refine vital seaweed compounds into pharmaceuticals, food and feed ingredients and precursors for biodegradable plastics for example
- CPI has developed specialist equipment for LightOx Limited to enable compound screening of molecules for the development of next-generation skin and oral cancer treatment drugs
- The BEACON pilot-scale facility helped develop a cost-effective and scalable method of producing Galanthamine – effective in the treatment of Alzheimer's disease – from daffodils, through a collaboration with Agroceutical Products Ltd
- IBioIC provided access to equipment for initial scale-up of algal biomass separation, extraction and filtration processes to help Scottish company Glycomar extract novel glycomolecules for use in the healthcare sector

Translating research into innovative products and technologies requires specialist facilities, which may be in 'challenge-oriented' or 'capability-oriented' centres and broader research and innovation campuses to ensure proximity to the right expertise and environments. Creating support for early translation will enable the development of a richer pipeline and pull-through. This could develop a seamless transition to the NIHR research infrastructure to continue the next phase of translation for patient benefit and economic growth. Facilities can:

- Provide flexible labs for joint academic/industry/NHS collaborative projects
- Deliver specific, early-stage capabilities; such as small-scale manufacturing and rigorous quality control processes to support experimental medicine trials
- Support prototyping and analytics, including complex pilot and demonstration-scale facilities and production-scale testing capabilities (see case study), with linkages to end-users and early adopters in the agri-tech, engineering or medical sectors

On a broader scale, centres and campuses can support the co-location of multiple state-of-the-art technologies, incubator space and expertise in responsible research, regulatory frameworks, legal requirements and business development that few universities or start-ups would have the capacity to assemble in isolation.

Theme 9: Synthetic biology and industrial biotechnology

The tools and technologies developed through synthetic biology, and the products and processes enabled by industrial biotechnology, will have significant impact on discovery research and industrial sectors ranging from agriculture to pharmaceuticals and will be essential to establishing a sustainable bioeconomy.

How this area can be progressed/indicative approaches

Specialist centres	Specialist centres would enable discovery science and the translation process through provision of state-of-the-art integrated facilities (to enable the design-build-test-learn cycle), including advanced technology platforms, automated pipelines and high-throughput approaches to development, prototyping and analytics. These could comprise new capability and capacity grounded in existing thematic multidisciplinary Synthetic Biology Research Centres, plus expansion to establish and build on other centres of critical mass, as well as DNA Foundries and coordinated industry-academic networks in industrial biotechnology.
Scale-up and production facilities	Development of scale-up and production facilities would enable the translation of new products and processes developed in the laboratory to industrial-scale manufacturing, including pilot- through to demonstration-scale facilities (e.g. fermentors) and production-scale testing capabilities, with appropriate linkages to end-users/early adopters.
International facilities and networks	Coordination and networking of the UK capability would enable access to international facilities and networks such as those provided by ESFRI projects, e.g. the European Industrial Biotechnology Innovation and Synthetic Biology Accelerator. This could be through an expansion of the Synthetic Biology for Growth and Synthetic Biology UK (SBUK) activities, plus the Networks in Industrial Biotechnology and Bioenergy.

Theme 10: Innovation infrastructures

Delivering a step-change in impact through the creation of new innovation infrastructures that host the right mix of technologies and expertise to successfully 'pull through' new innovation solutions from discovery science.

How this area can be progressed/indicative approaches

Accelerators/centres *Coordinated with industry, Innovate UK, EPSRC, the NHS and UK health departments*	Establishing new accelerators or centres would provide a range of focused capabilities to accelerate the development of emerging technologies, processes or treatments, bridging the gap to application. For example: ■ Challenge-focused: e.g. rare disease diagnostics and treatment, or net-zero agriculture and food production ■ Capability development and pre-competitive ('one step out of the lab') demonstrator facilities: e.g. synthetic biology tools and services such as those at the SynbiCITE synthetic biology accelerator, or creating regulated manufacturing facilities for prototype development and piloting innovations ■ Technology readiness centres: e.g. developing a technology for clinical use, such as 7T-MRI, or translation of biotechnology innovations into the marketplace, such as through the Centre for Process Innovation Priority areas could include: ■ Engineered cell-based therapies ■ Anti-infective industry partnerships ■ Implantables, neuroelectronics and nanotechnologies ■ Digital health care and developing AI for clinical use ■ Precision medicine, emerging diagnostic technologies or sensors
Campuses *Coordinated with industry, Innovate UK, EPSRC, UK government agencies and departments, the NHS*	Development of existing or new campuses focusing on development of critical mass with close proximity to key delivery partners/ users (academics, industry including farming, the NHS) would enhance access to incubator space, automated analytics platforms, scale-up facilities and technology development.

Theme 11: E-infrastructure for Life Sciences

The rate of data generation across all modalities is increasing and complex algorithms and methodologies are required to integrate diverse data types, presenting significant, strategic opportunities for data reuse, in deep learning and in other AI applications supporting the biosciences. A range of e-infrastructure solutions will be required to harness heterogeneous biological, clinical, population and environmental research data and link these with routine and real-world data, driving the need for research data infrastructures to integrate, analyse and share complex data sets.

Computing for the life sciences has specific requirements and accordingly tailored architectures, which are designed to enable memory-intensive parallel processing in addition to managing large volumes of data, integration with relevant biological databases and the use of data commons by dispersed collaborators. Of primary importance to this sector are large-scale Research Data Infrastructures configured to meet the specific requirements and complexity of the data types and processing necessary for research in the biological and medical sciences. The use of tailored HPC is now routine, for example when making sense of the petabytes of data generated by imaging, 'omics and genome sequencing technologies, or running biomolecular simulations. These research data infrastructures may serve a broad swathe of the community (academic and industrial) by providing access to a range of validated and well-curated data sets supported by interoperable systems and advanced analysis and modelling tools, such as at EMBL-EBI which services requests from 3.3 million unique sites and works with researchers in sixty-four countries. Other research data infrastructures may focus on a specific challenge such as food security at the Earlham Institute, where HPC is combined with expertise in bioinformatics, bioscience and statistics, and the processing capability needs to be physically located close to the experimental work generating the data.

Other e-infrastructures operate as distributed or virtual infrastructures, such as HDR-UK, which provides access to large-scale data and advanced analytics gathered from twenty-two partners across six regions, uniting the UK's health data to make discoveries that improve people's lives. These distributed e-infrastructures may extend beyond the UK and across Europe, as with ELIXIR which brings together life science data resources from twenty-two members located in twenty-one countries across Europe. ELIXIR comprises of a hub based in the UK, plus national nodes including a UK node (Chapter 8), and internationally as the UK hosts a node of CyVerse, a US-based cyberinfrastructure for life science research.

CASE STUDY: EMBL-EBI

The European Bioinformatics Institute (EMBL-EBI) is part of the European Molecular Biology Laboratory (EMBL), Europe's flagship laboratory for the life sciences and home of the world's most comprehensive range of freely available molecular data resources. EMBL-EBI's databases, tools and software support millions of researchers to share and exploit complex information efficiently to make ground-breaking discoveries, with over 64 million web requests received every day. Independent estimates suggest a year of research undertaken using EMBL-EBI data resources provides economic returns of £920 million annually[6].

EMBL-EBI serves as an anchor partner in many human health programmes covering disease progression and treatment, rare diseases, microbial resistance, and modelling infection outbreaks, as well as wider ventures to improve our understanding of biology, including marine systems, stable crops and biodiversity.

As the host of the ELIXIR hub which brings together data from across twenty-one member countries, EMBL-EBI additionally supports the wider coordination of biological data provision across Europe. It works in partnership with businesses from the pharmaceutical, agri-food, nutrition and healthcare sectors on pre-competitive collaborations. The largest of these partnerships, Open Targets, is systematically identifying and prioritising targets to use for development of safe and effective medicines.

EMBL-EBI

This sector also requires access to and sufficient capacity in high-capability computational infrastructure through national and international domain-agnostic facilities (Chapter 8). There is also the need for appropriate storage infrastructure and the ability to link and integrate different data types and sources, e.g. personal or health data, taking account of controlled access and security/encryption requirements, and the retention of data for reuse over long periods of time (e.g. for longitudinal cohorts). Following the FAIR[46] principles (to make data Findable, Accessible, Interoperable and Reusable) is fundamental to realising the scientific opportunities offered by data linkage/alignment, including reproducibility. UK-based institutions (for example, EMBL-EBI, UK Biobank and the Image Data Resource) have world-leading capabilities for collecting, integrating and publishing reference data sets for the global scientific community.

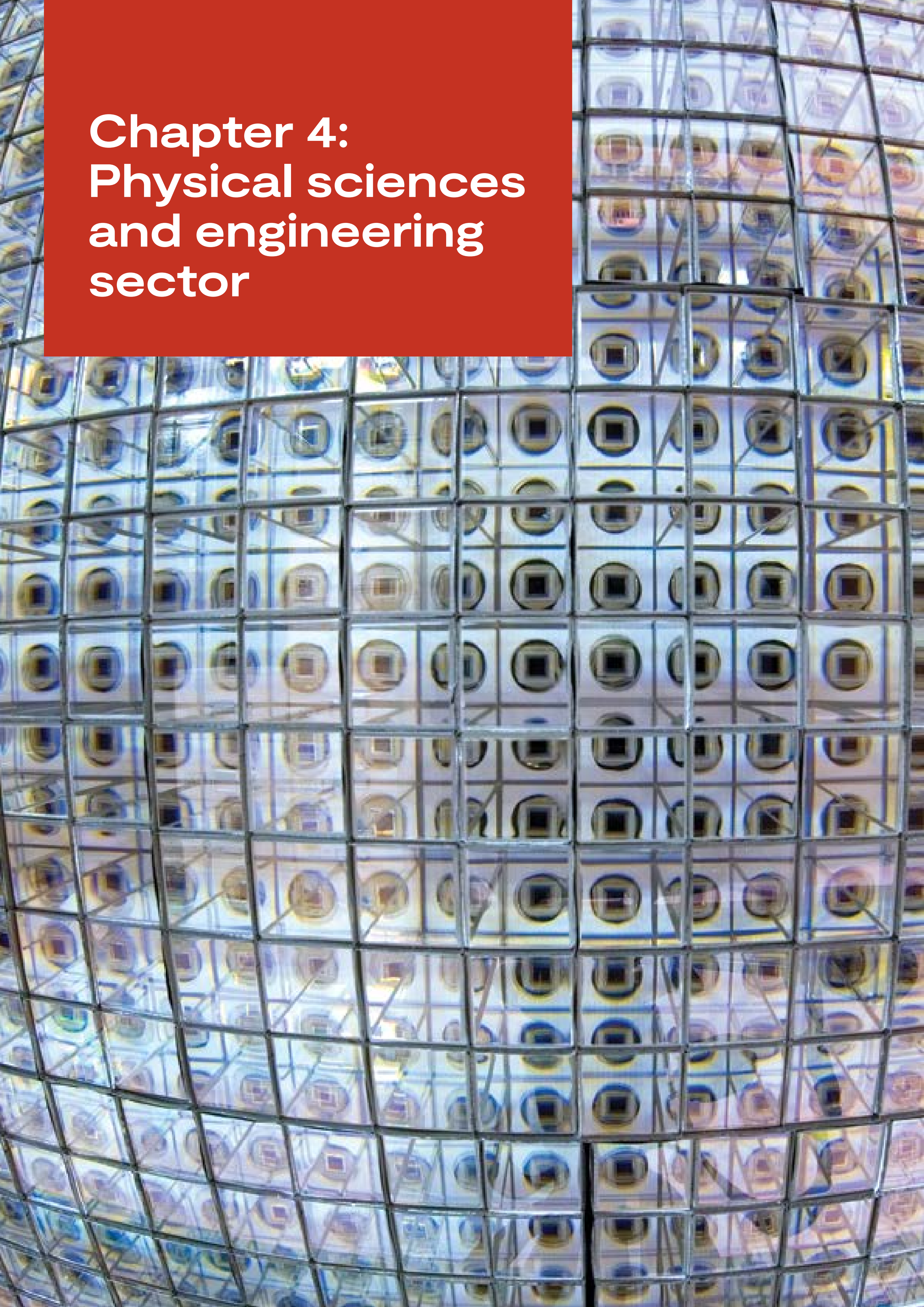
Theme 11: E-infrastructure for life sciences

The biological sciences, health and food sector needs access to varied and well-integrated e-infrastructure solutions to harness the diverse and vast sources of heterogeneous data and combine these with routine and real-world data. This includes a coordinated set of research data infrastructures and enabling services (software, people) to integrate, analyse, store and share complex datasets.

How this area can be progressed/indicative approaches

Biological sciences, health and food sector-specific research data platforms	Biological sciences, health and food sector-specific research data platforms tailored to support disciplines in the life sciences (e.g. synthetic biology, multiscale biology, animal/plant/human health, phenotyping, imaging, structural biology), would provide access to a range of validated data sets supported by interoperable systems and advanced analysis and modelling tools. Significant upgrades to existing capabilities would be needed on an approximate five-year cycle, which may require entirely new phases of development. Specific opportunities include: ■ Phase 2 of the EMBL-EBI Technical Infrastructure project to accommodate new archives to expand the first large-scale, open 'reference' archive for imaging data and develop new resources specific to serious global challenges (e.g. Antimicrobial Resistance, sustainable food production, biodiversity and personalised medicine) ■ Significant expansion of the UK node of ELIXIR to support BioFAIR, a data sustainability institute supporting the coordination and development of UK life science data ■ Additional platforms which will also be necessary for new challenge areas, e.g. AI centres for exploring biological data or mining population and cohort data

Chapter 4: Physical sciences and engineering sector



The physical sciences and engineering sector covers all branches of physics, chemistry and mathematics and includes materials science, information and computing technology, quantum technologies and engineering. Research in this area has application in healthcare technologies, the digital economy and manufacturing industries. Knowledge generation through to application, innovation and commercialisation in this sector directly supports delivery of the Industrial Strategy Grand Challenges and many of the Sector Deals, including those on automotive, AI, construction, nuclear and creative industries[47]. The breadth of infrastructures, aligned with expertise in technology development, provide opportunities for strong industrial collaboration.

From advancing our knowledge of the Universe to our understanding of new materials and chemical reaction dynamics and mechanisms, excellent research and innovation across this sector requires access to world-class research and innovation infrastructures. Advances in technology and digitisation are also vital to enhance capability in this sector and will provide the foundational aspects of many of the new technologies adopted within the food sector, life sciences, cultural heritage, Earth sciences and beyond. Innovations in the physical sciences and engineering sector will provide novel materials, new sensors and imaging modalities and novel analytical techniques.

Within UK Research and Innovation, three councils (Science and Technology Facilities Council (STFC), Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK) support the majority of research and innovation activity in the physical sciences and engineering sector. Other critical organisations in this sector include the UK Space Agency (UKSA), the National Physical Laboratory (NPL), the Atomic Weapons Establishment (AWE) and several government departments and agencies including the Defence Science and Technology Laboratory (DSTL). International collaborations and funding are particularly important in fundamental physics where the scale of the activity requires substantial investment from many partners and UK participation in large international projects is a key part of the government's International Research and Innovation Strategy[100].

4.1 Overview of current capability

The physical sciences and engineering sector includes a range of technologies and tools at all scales from distributed networks of imaging infrastructure to large-scale, single-sited infrastructures such as telescopes and lasers. In addition to university-based infrastructures there are a number of Catapults, PSREs and other government agencies that develop and operate infrastructure across this broad sector, from fundamental research infrastructures to higher Technology Readiness Level (TRL) demonstrators. The larger, multi-sector facilities are discussed in detail in Chapter 9 and are also significant contributors to the physical sciences and engineering landscape.

Infrastructures within this sector can be described as capability and discovery driven, application driven or challenge driven (Figure 10). To answer complex, interdisciplinary problems, a combination of approaches is needed that often make use of infrastructures across the different categories.

Given the different scales and types of infrastructure in this sector, the **interconnectivity** between high-quality, lab-based, distributed facilities and large-scale, campus-based facilities is particularly important. There are several successful equipment-sharing initiatives that have underpinned the development of **institution-based and distributed clusters of equipment or facilities that are managed as single infrastructures**, thereby ensuring more effective use. The ability to replace individual pieces of equipment within a cluster (examples from the capability and discovery category in Figure 10 would include NMR or mass spectrometers) might be within the means of a single institution or funder. However, the ability to concurrently refresh multiple items or make investments in larger-scale, next-generation systems on behalf of the whole UK community needs strategic decisions at a national level (Chapter 9). EPSRC's National Research Facilities (NRFs) are an example of how this is done in practice. NRFs support strategic resources of national importance to provide leading-edge capabilities and technique development at a national level in response to community need.

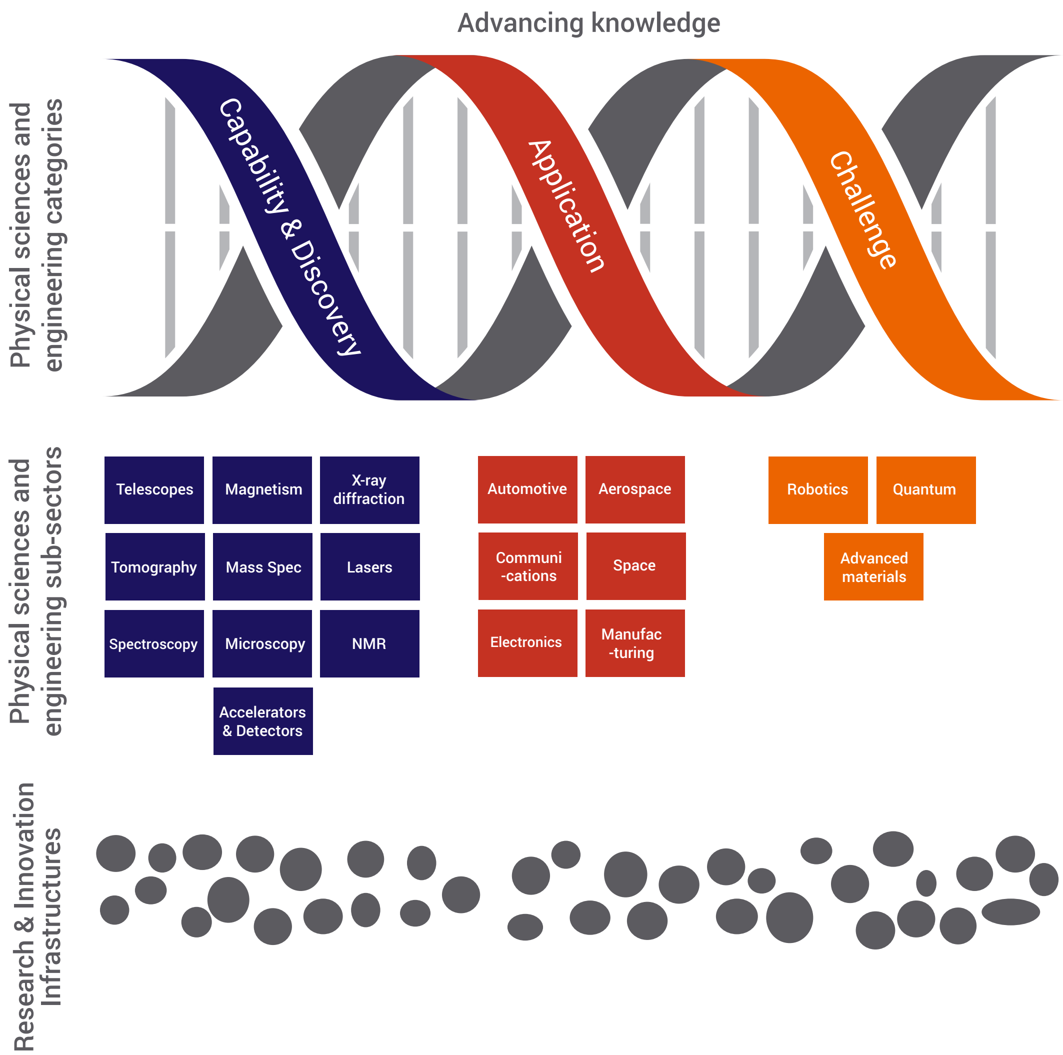
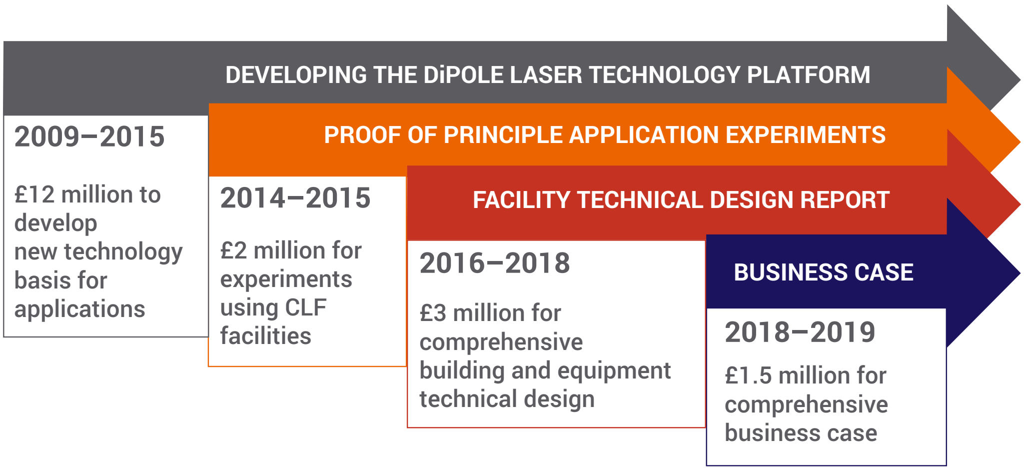


Figure 10. The classification and sub-sector grouping of the physical sciences and engineering research and innovation infrastructures.

In the Landscape Analysis, 27% of infrastructures cited physical sciences and engineering as their primary sector and there are strong interdependencies with the biological sciences, health and food, environmental sciences and energy sectors. **Many have an expected lifespan of over twenty-five years,** reflecting the size, complexity and significant investment typical of this sector. Such infrastructures often **involve decades of planning and investment** to identify the highest priorities and initiate planning and design phases before construction can begin. For instance, the complexity of the build of the Extremely Large Telescope (ELT) means that although plans were agreed in 2002, construction only started in 2014 and first operations are not expected until 2025. The design stages of large-scale infrastructures are often significant research activities in their own right involving the build or development of novel technologies and techniques as a precursor to developing the final infrastructure.

CASE STUDY:
Investment in design stages: Extreme Photonics Applications Centre (EPAC)

The BEIS and MoD funded (£81 million) EPAC, based at the Harwell Campus in Oxfordshire, will explore the development and application of novel accelerators and associated energetic particle/radiation sources using lasers. The project took a number of years to evolve, requiring substantial conceptual funding through government, external partnerships and commercial arrangements.



4.2 Future direction

As with all other sectors, successful infrastructures need to enable cutting-edge research using state-of-the-art equipment, in the right place and underpinned by well-qualified technical support. In the physical sciences and engineering sector, developing **networks of facilities that bridge the gaps from smaller-scale infrastructures to large facilities** will be important to ensuring more effective use is made of mid-range to large-range investments. Encouraging such connectivity should help to develop the technical and analytical expertise that is needed to maximise the productivity of infrastructure investments and enhance the quality of the experimental outputs.

Continuous technical advancements are required to improve how we undertake research due to the increasing complexity of physical sciences and engineering infrastructures, extremely large data rates, challenging/extreme environments and the need for greater technical and analytical expertise to deliver complete systems. Taking an active role in building novel technology for UK and international infrastructures adds to our competitive edge when participating in the highest-priority international ventures.

With the availability of increasing computational power, large-scale numerical models for physical phenomena and 'digital twins' for complex products and systems, we will require increasingly sophisticated experiments and observations for their calibration and validation. Large research and innovation infrastructures by their nature create large data sets; therefore, continuing to develop the skills and capacity and **state-of-the-art e-infrastructure** to meet the demand of the data production and analysis volumes is essential for this sector.

This report focuses on opportunities for step-changes in capability through new infrastructures or major upgrades to existing capability. However, it is also **important to support existing capability** to maintain the UK's leading position in technology development (e.g. accelerators and detectors), application, monitoring, observation and scientific discovery (including national institutes).

Maintaining **UK participation in international physical sciences and engineering infrastructures** is a vital part of securing access to the next-generation of capabilities. There are continual upgrades at international facilities supported by the UK and where UK expertise plays a critical role. For example, there are numerous upgrades in progress to support the particle physics programme at the European Organisation for Nuclear Research (CERN). This involves extensive research and development and major construction programmes, e.g. the

ATLAS and CMS detector upgrades. The Large Hadron Collider beauty experiment (LHCb) and A Large Ion Collider Experiment (ALICE) (ALICE) collaborations are also planning major detector upgrades. Programmes such as these for detector research, development and construction in particle physics and similarly for telescope instrument construction (e.g. the ELT) for astronomy, are very important contributions to the international science infrastructure with significant technical and engineering work undertaken in UK universities, national laboratories and industry.

Support for community engagement, conceptual design, R&D and prototyping to improve existing or create new infrastructures is particularly critical in this sector where infrastructures are often large and technically complex. Such studies are significant research activities in their own right, often involving the build or development of novel technologies and techniques as a necessary precursor to developing the final infrastructure.

4.3 Future requirements and opportunities

Consultation over the course of this programme has identified six key themes that could shape the direction of physical sciences and engineering infrastructures over the next ten years and beyond. These themes have been updated to incorporate feedback received and additional work done since the publication of the Progress Report. Within each of the themes, we present some potential opportunities for future infrastructure capability with illustrative examples. These have been identified through a number of routes including programme evaluations, community workshops and reviews of UK, European or global roadmaps.

The scale of opportunities within the physical sciences and engineering sector varies widely and opportunities for UK partnerships or national research and innovation infrastructures will change over time. The themes present challenges that can be addressed through a number of routes and it will be important for the UK to connect to other international roadmaps and activities.

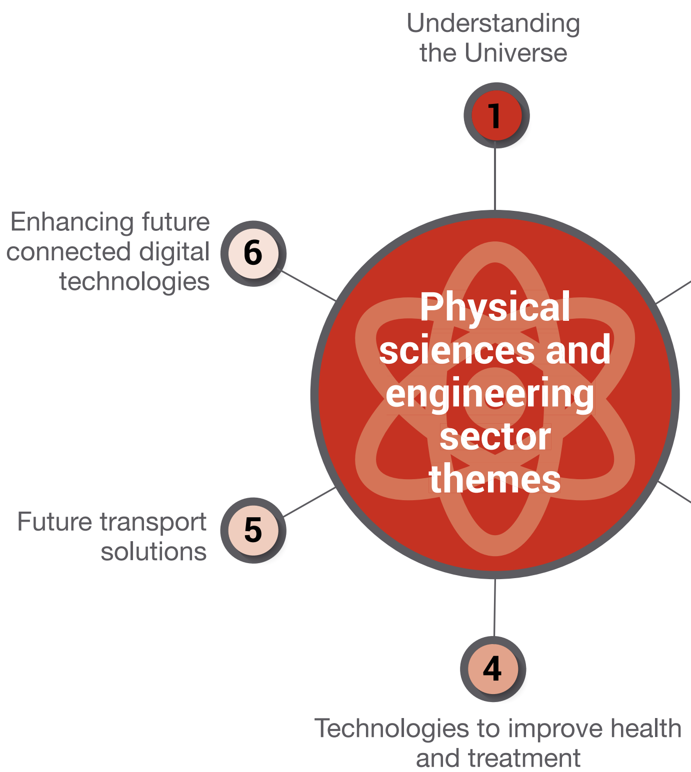


Figure 11. Physical sciences and engineering themes overview.

As described in Chapter 2, Section 2.4 the opportunities for future infrastructure capability described within the themes are at different stages of development. Some ideas need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered whilst others are more developed and could be implemented sooner. The landscape is fluid and opportunities will arise during the next few years while some opportunities will become less relevant or superseded. Scientific peer review and community consultation will allow us to gauge support and to tension opportunities. There will also be significant upgrades to existing capabilities that have not been captured here as they are beyond the timeframe of this report, e.g. Square Kilometre Array 2.

Theme 1: Understanding the Universe

Research in particle physics, particle astrophysics, astronomy, space science and nuclear physics seeks to understand the Universe from the largest astronomical scales to the fundamental building blocks of matter. Advancing knowledge in frontier physics will require UK participation in R&D to design, construct and eventually exploit new experiments, as well as upgrades to existing experiments such as the High-Luminosity Large Hadron Collider (HL-LHC). The scale of the infrastructures needed for such experiments will involve long-term planning and commitments to international collaborations. Examples of current international projects with UK participation, set to begin operations in the coming decade after many years of planning and implementation, include Square Kilometre Array (SKA), Extremely Large Telescope (ELT), the Large Synoptic Survey Telescope (LSST) and the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) in the USA. The technological challenges to overcome will create opportunities for research and industry collaboration with the potential for wider application of technologies in industry sectors such as advanced manufacturing and healthcare.

Subtheme: How did the Universe begin and how is it evolving? How do stars and planetary systems develop and how do they support the existence of life? Adding knowledge of the structure and constituents of the Universe reveals deeper questions and mysteries about how nature fits together. Understanding the beginnings of the Universe takes us from exotic conceptual theories of physics to experiments underground trying to detect dark matter, and from state-of-the-art mega-simulations of galaxies forming and evolving to space missions attempting to understand the nature of dark energy. The goal of understanding our origins encompasses all areas of theory, experimentation and observation, and can truly be considered a fundamental scientific challenge.

We know that microbial life can survive in hostile and extreme environments such as deep-sea geothermal vents. The consensus now is that where there is water, nutrients and an energy source such as our Sun, there is the possibility for discovering life. The obvious first place to search for extraterrestrial life is within our own solar system. Possible examples include Mars, which may have regions in its permafrost that could harbour microbial communities, and in the subsurface water ocean of Jupiter's moon Europa.

Satellites and telescopes are now discovering thousands of planets orbiting other stars in our galaxy. These new observations are revealing many exoplanet systems, which will help us to place our solar system in a wider context. Studying them will help us understand how common solar systems like our own are and how many exoplanets might be capable of supporting life. We may even be able to recognise the existence of life on these distant worlds.

Subtheme: What are the basic constituents of matter and how do they interact? There are still many challenges remaining. Why is there so little antimatter in the Universe? How did the Universe evolve from the Big Bang to now? What is dark matter made of and how does it behave? Above all, we want a deeper and more complete understanding of our universe at these most fundamental levels.

There are significant e-infrastructure needs that support this theme, including essential upgrades to existing HPC and HTC infrastructures, such as Distributed Research using Advanced Computing (DiRAC) Facility (Chapter 8, Section 8.1). New potential infrastructures, such as a supercomputer that would be a step towards an exascale system, would ensure outputs from the physical sciences and engineering sector can be maximised.

Theme 1: Understanding the Universe	
Subtheme: How did the Universe begin and how is it evolving? How do stars and planetary systems develop and how do they support the existence of life?	
How this area can be progressed/indicative approaches	
Ground-based observational astronomy	UK participation in international collaborations to construct new telescopes would enhance UK astronomy capability. There are several options such as: the Simons Observatory for observations of the cosmic microwave background, to understand the conditions of the very early Universe better; the European Solar Telescope to observe and model the physical processes in the solar atmosphere, providing detailed understanding of the Sun's activity and its impact on space and Earth; the New Robotic Telescope which could provide UK leadership in time domain and solar system physics, such as the discovery and characterisation of extrasolar planetary systems; and the Gravitational Wave Optical Transient Observer (GOTO) which could improve the ability to localise the sources of gravitational wave events.
Gravitational Wave observatories	The Einstein Telescope is a proposed third-generation Gravitational Wave (GW) observatory in Europe and one of the highest-priority projects on the Astroparticle Physics European Consortium roadmap. As the second-generation of GW detectors reach their limits, the Einstein Telescope would ensure GW observing capacity for the coming decades, while at the same time increasing instrument sensitivity. This would allow us to map GW sources through the different ages of the Universe to answer questions about the nature of black holes and neutron stars. The Einstein Telescope is expected to be constructed and operated as an international organisation, with site selection estimated to take place in 2021/22 and construction to commence in 2024.
Next-generation particle astrophysics infrastructures	Participation in one or more international particle astrophysics infrastructures would complement the UK's existing capabilities and fill gaps in the research portfolio. Opportunities for the UK include: high-energy astrophysics with one of the next-generation of gamma-ray observatories such as the High-Altitude Water Cherenkov Observatory, the Southern Gamma-ray Survey Observatory, or the Cherenkov Telescope Array; astrophysical neutrino observatories; the Atomic Interferometric Observatory and Network to probe as-yet mostly unexplored frequency bands of the GW spectrum; and the next-generation of direct dark matter searches.
Lunar Orbital Platform Gateway	The Lunar Orbital Platform Gateway is a collaboration between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and other international partners. It would provide a facility and infrastructure for learning how to live and work in deep space and a staging post for lunar activities, as well as offering a range of opportunities for science in deep space. The European contributions to this endeavour would be the provision of the service module to the Orion vehicle that would transfer the astronauts to and from the Gateway, and component parts of the Gateway structure. The first modules are expected to be flown in the mid-2020s.

How this area can be progressed/indicative approaches *cont.*

Mars Sample Returns	An international campaign led by NASA with collaboration from ESA to collect material from the surface of Mars and return it to earth. The mission has long been one of the highest priorities for planetary science, but it is only now that we have the technical capability to implement it. NASA will launch the ascent vehicle in either 2026 or 2028 with the samples being returned in 2031 or 2033. The main curation facility for the samples returned is provisionally planned for the USA, but there is an opportunity for the UK to host a secondary curation facility that will host a second set of back-up samples for archiving, should there be issues with the primary facility such as contamination episodes. This could have significant multidisciplinary applications across life sciences and geological sciences.
Next-generation space science and exploration missions	ESA is planning a programme of future space missions through its Cosmic Vision and Voyager 2050 programmes. There are opportunities for the UK to provide significant contributions to these missions, building on excellence in scientific techniques and novel technologies. There is also potential for UK space science and space exploration programmes through bilateral agreements, to participate in missions with non-European space agencies, such as NASA, the Japanese Aerospace Exploration Agency and the China National Space Administration.

Subtheme: What are the basic constituents of matter and how do they interact?

How this area can be progressed/indicative approaches

State-of-the-art nuclear physics facilities	The UK could participate in new nuclear physics experiments at international facilities, such as CERN, the Facility for Antiproton and Ion Research, the University of Jyväskylä, the Jefferson Laboratory and the RIKEN research institute. In all cases this would bring opportunities for the UK to develop and implement detector technologies which capitalise on the UK's world-leading expertise and address key scientific questions in the area of nuclear structure and astrophysics. There are a number of options including an upgrade of the Advanced Gamma Tracking Array or an Advanced Charged-Particle Array.
Next-generation Electron Ion Collider	The Electron Ion Collider in the USA will be the world's first doubly polarised electron-nucleon/light-ion collider and the world's first electron heavy-ion collider. The new facility is expected to commence operations around 2030, providing variable centre-of-mass energies and high luminosities. UK involvement would give unprecedented access to the structure of nucleons and nuclei, exploiting the nucleus as a laboratory for the study of quantum chromodynamics.

How this area can be progressed/indicative approaches *cont.*

Next-generation particle physics experiments	To ensure continued UK leadership in key international particle physics experiments over the next two decades would require UK participation in the development of research infrastructures at international facilities such as CERN (Switzerland), Fermilab and the Sanford Underground Research Facility (USA), the Paul Scherrer Institute (Switzerland) and the Japan Proton Accelerator Research Complex. The opportunities and future landscape will be continuously reviewed by the STFC advisory panels.
Next-generation particle physics colliders	The future direction of the energy-frontier programme beyond HL-LHC will push the boundaries of our current understanding of the Universe. The scale and complexity of the next large-scale colliders requires planning now. Options being considered include: an energy upgrade for the LHC (HE-LHC); a new electron-positron linear collider, which could be either the International Linear Collider in Japan or the Compact Linear Collider at CERN; the Future Circular Collider at CERN; or the Circular Electron Positron Collider in China. UK participation would be guided by the update to the European Strategy for Particle Physics in 2020 led by CERN.
Boulby Underground Laboratory capability	The Boulby Underground Laboratory in Yorkshire is the UK's large, deep underground physics laboratory. There is an opportunity to exploit the recent investments in this facility by hosting a large-scale international experiment in the UK, such as a next-generation dark matter experiment or a neutrinoless double beta decay experiment.

Theme 2: Novel technologies for the next-generation infrastructures

Advances in detectors and receivers, instrumentation, accelerator science, specialist engineering and optics are needed to enhance existing and build new world-leading physical sciences and engineering infrastructures. These advances can have wider applications across other sectors. The UK is at the cutting edge of technology development in these areas and innovations developed by UK scientists, engineers and technologists are frequently sought-after internationally.

Subtheme: Developing advanced technologies. Development of new technologies including detectors and instrumentation also requires dedicated infrastructure and can put the UK at a competitive advantage. Enhanced capability to develop technologies including detectors, sensors and optics, for example, would also stimulate the development of feasibility studies and pump-priming activities to enhance future infrastructure developments.

Subtheme: Advanced characterisation and imaging. Developing the next-generation characterisation and imaging infrastructures will be inherently interdisciplinary, supporting academia and industry across health, aerospace materials, nuclear materials and semiconductor devices. This requires small- and large-scale instrumentation to help understand and correlate materials at different length scales, from atoms to components. In some areas, intermediary facilities are needed to support precursor studies, analyses, sample preparation and user training and bridge the gap between local capability and larger facilities.

Case Study:
Xspress4 pulse processor

Diamond Light Source (Diamond) and STFC staff worked together to develop the next-generation of pulse processor: Xspress4. Synchrotrons like Diamond use techniques such as X-ray Absorption Fine Structure (XAFS) to examine the structure of materials at the atomic scale. Pulse processors enhance the throughput of the semiconductor detectors used at the facility for XAFS experiments by a factor of two to three and enhance data quality. This gives Diamond a competitive advantage, allowing analysis of very challenging samples that could not be analysed before and making better use of the X-ray beam time due to the improved counting rate of the detector. The Xspress4 pulse processor will be commercialised by Quantum Detector, a spinout company from STFC and Diamond.

The Xspress4 pulse processor.

Graham Dennis at Diamond Light Source

Theme 2: Novel technologies for the next-generation infrastructures

Subtheme: Developing advanced technologies

How this area can be progressed/indicative approaches

Novel prototyping and fabrication facilities	Requirements for new and advanced technologies are already emerging from the space sector and the users of large-scale national facilities such as Diamond and the ISIS Neutron and Muon Source. The development of these technologies would require dedicated new prototyping and fabrication facilities. One such opportunity would be a facility for multilayer fabrication and characterisation. Examples of research applications include niche optical coatings, coatings for superconductors, active pumping surfaces and corrosion- and wear-resistance surfaces. Furthermore, engineered surface properties are important across a growing number of application areas (accelerators, sensor materials, quantum systems) and access to fabrication facilities will significantly increase the opportunities for academic innovation and speed up industrial uptake. Extending novel fabrication from 2D to 3D microstructures would also give opportunities to support next-generation target fabrication, enabling new realms of high-energy density science to be explored as well as new applications of high-average-power lasers, such as carbon ion radiotherapy and neutron analysis of buildings.
Development of a novel accelerator systems test bed	There is increased interest in novel particle accelerator technologies which address key scientific questions across multidisciplinary areas, from energy-frontier particle physics experiments to diagnosing and treating tumours.

How this area can be progressed/indicative approaches *cont.*	
Development of a novel accelerator systems test bed *cont.*	A new UK novel accelerator centre would build on existing UK expertise through investment in laser, plasma and dielectric particle accelerator techniques that could revolutionise the many uses of accelerators in science and technology. The centre could be either a single entity or distributed and could include free-electron laser technologies. Expert advice will be sought on future options and priorities.
Detector Systems Hub	In recent years, the UK's large-scale national facilities, such as Diamond, have made substantial advances. In order to fully exploit our facilities, tomorrow's instrumentation systems require matching development to meet the increases in accelerator brilliance and dynamic range. A new Detector Systems Hub would provide a national focus for the development of next-generation instrumentation systems. The facility would ensure continued UK technical leadership in the discovery, development and application of novel and innovative detector and sensor technologies for applications in fundamental and applied science.
Development of lab-based mid-range facilities of national importance: accelerator-driven, low-energy light source	Exploiting the complementary capabilities of two light sources – Free Electron Lasers for Infrared eXperiments (FELIX) in Nijmegen and the Accelerators and Lasers In Combined Experiments (ALICE) accelerator at Daresbury – would enable creation of the Advanced infrared/Terahertz Facilities for Users of Lasers (ARTFUL). The two suites of free-electron light sources have complementary capabilities. Combining them into a single, distributed facility would create a single community and enable users to develop research programmes benefitting from access to both sources.
Development of lab-based mid-range facilities of national importance: ultrafast dynamic imaging	Development of a national facility centred on the unique measurement capabilities offered by Relativistic Ultrafast Electron Diffraction and Imaging (RUEDI). RUEDI allows the evolution of structural changes in materials to be observed through time-resolved pump-probe experiments. A new facility would be unique in the UK by allowing the function of a material to be determined, rather than simply its static structure. A RUEDI facility would provide a conduit from the study of fundamental materials and biological processes to the advanced technologies associated with them.
Advanced imaging	Development of a facility of national importance in X-ray Computed Tomography would sit at the heart of the UK's physical sciences and engineering research and innovation infrastructure portfolio, supporting the rapid maturation of advanced materials and other fields.
Future capability for mass spectrometry	Work is needed in consultation with the community to identify the specific opportunities for significant technique development and define a coherent national effort. This would enable a more coordinated programme of upgrades to national and regional facilities, better utilisation of local facilities and greater collaboration across sectors.

Subtheme: Advanced characterisation and imaging

How this area can be progressed/indicative approaches	
Ultra-high-field NMR facility: the UK's first national NMR spectrometer with field strength in excess of 1.0GHz	Continued investment in world-leading NMR facilities would provide a toolkit that would enable new scientific breakthroughs. It would allow scientists to study molecules (their structure and how they move, behave and interact) in more detail than is currently possible, supporting fundamental and applied research in the UK across a range of disciplines including chemistry, engineering, biosciences and medicine.
Enhanced provision for characterisation and imaging techniques of national importance	National Research Facilities are providing access to a wide range of state-of-the-art equipment, specialist analysis and training for academic and industrial users in a sustainable way. They play a key role in the interconnectivity between lab-based, distributed facilities and large-scale campus-based facilities. There is an opportunity to enhance and refresh our portfolio of these facilities to ensure that they continue to provide access to state-of-the-art facilities for the widest possible range of users, for example in techniques such as Electron Paramagnetic Resonance and X-ray crystallography.
Acquisition of instruments to perform cutting-edge photo-electron spectroscopy experiments at the national level	Photo-electron spectroscopy is a powerful and versatile analytical technique with multiple applications, as well as being a research area in its own right. It enables the characterisation of surfaces and interfaces and as such underpins research activities across a broad user community including chemistry, engineering, physics, biology, materials science, bioengineering, pharmacy, environmental sciences and life sciences. Guided by the photo-electron spectroscopy community roadmap[48], there is an opportunity to invest in instruments which would be capable of performing photo-electron spectroscopy experiments at the national level.

Theme 3: Catalysing productive and clean growth

The ability to deliver a more agile, creative and internationally competitive UK economy can be enhanced through new discovery research, alongside investments to accelerate knowledge exchange and commercialisation.

Subtheme: Manufacturing futures. Advances in industrial digitalisation and automation have the capacity to transform manufacturing processes, enhancing the competitiveness of the UK industrial base. The government's Made Smarter[49] review highlighted the importance of industrial digital technologies to the global competitiveness of the UK's manufacturing sector. Increasing automation across the economy in, for example, transport, extreme environments, manufacturing and construction may produce important economic and social benefits. Through the Industrial Strategy, investment is being made in manufacturing research of immediate importance to UK industry. However, there is still a need for research with a longer time horizon, which is essential for developing new ideas, concepts and technologies and ensuring that they are pulled through into applications to support the emergence of new UK industries.

Subtheme: Commercialisation and application of quantum technologies. We want to make the UK the first choice as a place to research, innovate and commercialise quantum technologies. This requires the development of a quantum technologies ecosystem to enable the full supply chain for delivering quantum technology systems that will disrupt the semiconductor, oil and gas, construction, telecommunications and computing industries[50]. Quantum technologies that are currently being developed may lead to:

- More secure communications
- Resilient navigation – seeing through fog, rain, snow and around corners
- Better brain imaging

- Improved construction productivity
- Aiding the discovery of new oil and gas reserves
- Providing new quantum computers which can solve complex problems[51]

The construction of commercial, large-scale practical quantum computers is a significant challenge. Quantum computers being built by Google and IBM are expected to demonstrate hardware which for the first time can outperform the best classical computers at certain special tasks and simulations within the next one to two years.

Subtheme: Realising the potential of physical sciences and engineering. In the engineering and physical sciences landscape, national institutes provide a platform for longer-term, multi-organisation activities and play a leading role in the development of the research base and the technologies derived from it. In recent years, there have been a number of different types of institutes established including:

- The Alan Turing Institute, the national institute for data science and AI
- The Henry Royce Institute, the national institute for advanced material research and innovation
- The UK Collaboratorium for Research on Infrastructures and Cities (UKCRIC)
- The Rosalind Franklin Institute, focused on transforming life sciences through interdisciplinary research and technology development
- The Faraday Institution, the UK's independent institute for electrochemical energy storage science and technology, supporting research, training and analysis

Opportunities to scope the development of new activity will be explored.

CASE STUDY:
Henry Royce Institute

Researchers from the Henry Royce Institute acted as expert witnesses for GlaxoSmithKline plc in a recent patent dispute. They used state-of-the-art electron microscopy to map particles in an inhaler powder to treat progressive lung disease. This collaboration allowed GlaxoSmithKline to successfully defend the patent and has stimulated further research with the UK pharmaceutical industry in the application of microscopic imaging and analytical method to these materials.

The Henry Royce Institute has been set up to accelerate the invention and take-up of new materials systems that will meet global challenges, enhance industrial productivity and competitiveness and shape the world around us.

The Henry Royce Institute

Theme 3: Catalysing productive and clean growth	
Subtheme: Manufacturing futures	
How this area can be progressed/indicative approaches	
Digital manufacturing centres of excellence	It is essential that new ideas, concepts and technologies are pulled through into application to support the emergence of new UK industries. We want to ensure that manufacturing research with a long time horizon can build on the excellence of UK discovery science. Working in collaboration with the Connected Everything Network Plus and other stakeholders, we will explore specific infrastructure needs in this area with a view to developing academic-led, distributed, digital manufacturing centres of excellence. These centres would ensure that technologies emerging from our research base are developed with manufacturing in mind and will take a systems approach that focuses on the integration of technologies.
International stress engineering centre	Residual stress is a major cause of problems in manufacturing, leading to failures in infrastructure such as trains, planes and power stations. A new centre would support UK industry with multiple investigative techniques to characterise and model complex engineering components and structures. It would provide capabilities for measuring strain, stress and damage in materials ranging from the nanoscale to structures that are ten times heavier than any other facility worldwide could deal with.

Subtheme: Commercialisation and application of quantum technologies	
How this area can be progressed/indicative approaches	
Community-driven capability mapping across the advanced fabrication landscape – including semiconductors and quantum technologies	Our consultations have highlighted a lack of state-of-the-art capacity, in particular for new users, and a need for national coordination to encourage sharing of facilities and to take advantage of potential efficiencies. However, the landscape and future needs are not yet well understood or articulated. We will support the community to conduct detailed work to identify the current landscape and future national infrastructure needs to enable reliable, reproducible micro- and nano-fabrication.
National Quantum Computing Centre	Creation of a National Quantum Computing Centre would provide a centre of excellence to develop tools, computational algorithms and applications software to accelerate the practical application of quantum computing. This would seek to make the UK a leader in this emerging field, as well as providing access to a state-of-the-art quantum computing facility for the academic and commercial community. The long-term aim would be to host a practical application of quantum computing in the UK.

Subtheme: Realising the potential of physical sciences and engineering	
How this area can be progressed/indicative approaches	
Scope future national institutes in physical sciences and engineering	New national institutes would allow the UK to leverage and build world-leading research strengths by drawing together people, expertise and facilities across institutional boundaries.

Theme 4: Technologies to improve health and treatment

Healthcare systems are under pressure from a number of issues including an ageing society, mental and physical health concerns and an increasing focus on personalised medicine. Physical scientists and engineers, working in partnerships with the wider health and social care community, develop innovative techniques and technologies for adoption into UK and international healthcare systems to improve patient outcomes. Future opportunities to achieve this include:

- Advances in the diagnostic capabilities of imaging technologies such as MRI and tomography
- Discovery and design tools, synthetic developments and manufacturing approaches for future therapeutic agents
- Facilitating frontline healthcare professionals in innovation and evaluation centres to rapidly develop and iterate technologies for adoption
- Working with healthcare providers to explore appropriate solutions that transfer some of the service provision burden away from primary care settings and into people's daily lives
- Developing affordable and inclusive technologies that support people to live a healthier life in the home, workplace or wider environment to prevent ill health and further reduce pressure on many parts of the NHS

Physical sciences and engineering research is critical to much of the technological innovation that could be applied to healthcare and address the Ageing Society Grand Challenge, as well as providing the underpinning AI technologies to transform the prevention, early diagnosis and treatment of chronic diseases as outlined in the AI and Data Grand Challenge. Recent investments[52] in breast cancer detection research using innovative, portable, low-cost technologies for clinical analysis show how technologies can be adapted for use in other sectors. Future investments might focus on technologies for healthcare provision outside of the clinical setting or fully automated assistive technologies that support independent living and ongoing care needs (Chapter 3). These activities will be supported by development of technologies and innovation opportunities to maximise the impact of the research on people's lives and the wider economy. Such technologies will also support the social sciences, arts and humanities sector by aiding the development of systems for improving healthcare workflow or efficiency for the next-generation of public services.

CASE STUDY:
Cardiff University Brain Research Imaging Centre (CUBRIC)

CUBRIC is redefining the MRI scanner as a quantitative microstructural measurement tool. CUBRIC reduces sources of variance and bias and improves the diagnostic capabilities of this widely used healthcare technique. Funding from UK Research and Innovation (EPSRC, MRC) allowed the development of the National Microstructural Imaging Facility – one of only three in the world – as a user facility accessible to researchers across the UK.When combined with other facilities at the centre, including the UK's largest HPC cluster dedicated to neuroimaging applications, this creates a globally unique hardware platform to develop this new measurement science. This cutting-edge capability has attracted three holders of prestigious international fellowships to the UK to develop the technology further.

Paul Allen at Cardiff University

Theme 4: Technologies to improve health and treatment

How this area can be progressed/indicative approaches

Healthcare technologies innovation and evaluation centres	There is an opportunity to establish shared environments that would allow academics, health professionals and other partners to work together and iterate physical sciences and engineering-driven healthcare technologies, explore integration with other innovations and prepare for wider health sector roll-out. A first step would be to explore requirements in consultation with the community and develop a strategy to realise healthcare technologies innovation and evaluation centres.
Healthcare capability to underpin delivery of healthcare in the home, including diagnosis and treatment	Access to healthcare through primary care routes are under significant pressure, partly due to an ageing population. There is an opportunity to develop technological solutions that would transfer appropriate healthcare activity away from the established primary care settings and into people's homes. The potential areas for focus are broad-ranging, such as diagnostics, patient compliance, therapeutic manufacturing in the home and rehabilitation technologies. The specific focus of any activity that will help to deliver the maximum potential benefit on a large-scale investment is therefore currently unclear. A first step would be to explore and identify specific infrastructure options through engagement with the community.
Fully automated assistive technology capability, supporting complex and changing care needs	Health and care needs are requirements of every individual and are constantly changing. For an efficient health and care system, monitoring and provision cannot be limited to primary care providers alone. There is an opportunity to innovate technological solutions that provide support, assistance and care wherever and whenever required, in either the home, the workplace or environment. This has the potential to span aspects from robotic prosthetic devices to community-level sensing and monitoring for mental health distress. A first step would be to explore and identify specific infrastructure options through engagement with the community.
Advanced imaging: MRI scanner with magnetic field >10T	Higher magnetic field strengths provide improved spatial and temporal resolution, greater sensitivity to physiological changes and access to new contrasts, which will unlock a new era of imaging in precision medicine allowing more complex biomedical questions to be investigated. Investment in state-of-the-art infrastructure would support the development of the novel technologies and image processing methodologies required to enable the benefits to be realised, including cascading the developments to lower-field instruments to improve wider efficiencies.

Theme 5: Future transport solutions

We are on the cusp of a profound change in how we move people, goods and services around our towns, cities and countryside. Significant investments are being made: in the electrification and automation of road vehicles; in the modernisation of rail services to deliver higher capacity, speed and connectivity; and in the development of autonomous aerial and marine transport. There is a need to consider both improvements to existing transport infrastructure and modalities, and how best to implement disruptive new technology (such as connected and autonomous vehicles).

Physical sciences and engineering research has an important role in improving many aspects of our transport systems:

- Vehicle efficiency
- Energy storage
- Future fuel solutions
- City planning
- Charging infrastructure
- Physical and cybersecurity

Decarbonised transport and automation will be at the heart of this revolution. Developing more environmentally sustainable, responsible and carbon-neutral travel through electrification, based on new materials, novel technologies and seamless systems integration, will be a priority. Such step-changes to reduce carbon emissions and other pollutants will contribute to the Future of Mobility Grand Challenge and ensure the government strategy for zero-emission road transport can be achieved.

We want to build on existing R&D investments that have allowed the UK to remain at the forefront of aerodynamic and fluid mechanics research such as the distributed network of wind tunnels that are currently managed collectively as the National Wind Tunnel Facility. Increasingly, the role of wind tunnels (and other large test infrastructures) is not so much to test the scaled physical model but to obtain test data that allows model validation so that more of the design and validation can be done by computational modelling (such as creating digital twins) rather than by experimental means.

The need for test beds and demonstrators at higher TRLs will be addressed in part through some recently announced activities such as the ISCF challenges. With such large-scale experiments there will be many opportunities for the research and innovation community to conduct world-class activity in areas such as algorithm development, sensor design and energy storage solutions.

Theme 5: Future transport solutions	
How this area can be progressed/indicative approaches	
Electrified transport	Developing truly sustainable, responsible and carbon-neutral travel through electrification, based on new materials, novel technologies and systems integration. Electrification across all transport sectors has many similarities but also many significant differences, therefore it is not clear which infrastructure requirements are common and which are unique to specific transport sectors. This is an early-stage idea and the next step would be to develop the understanding of what gaps still exist for research and innovation infrastructures across the transport system with relevant stakeholders, including academia, the Faraday Institution and the Department for Transport.
National Wind Tunnel Facility	An existing capital investment of £14.5 million in 2015 developed and upgraded a suite of seventeen national wind tunnel facilities to provide a service that is greater than the sum of its individual tunnels and researchers. The next phase of investment would provide a testing and expertise infrastructure driving a paradigm shift in the way experimental research is approached, creating a strategically important infrastructure as recommended in the community wind tunnel roadmap[53].

Theme 6: Enhancing future connected digital technologies

The UK has a strong track record of developing innovative computational, communications and electronic technologies, building on foundational strengths across engineering and the physical, computational and mathematical sciences. We are world leaders in AI, data analytics, communications networks, mobile technologies, next-generation electronic hardware and materials, alongside research at the interface between these technologies and society.

Subtheme: Powering future digital technologies. As technology and power use continues to grow, we need more energy- efficient ways of designing, controlling and powering a diverse range of technologies. Incorporating an improved understanding of energy demand management into current technology development will have a significant impact. Research into materials, power storage, electronics design, networks, control and programming could also be transformational.

Subtheme: Developing living labs and digital twins. The intersection of technologies such as robotics and AI is driving the evolution of smart mobile machines, powered by clean energy, that are aware of the world around them and able to interact with it, with one another and with people. Many of the challenges of exploring the future of mobility, robotics and urban planning in situ can be overcome through the use of living labs and digital twins. As well as being a safe testbed, living labs and digital twins would also be an invaluable source of data for researchers, policy-makers, public planners, regulators and product and service suppliers. Any investment in these infrastructures should encompass the underpinning data archive that gathers and curates the data generated, making it available in interoperable formats across platforms for secondary analysis and modelling.

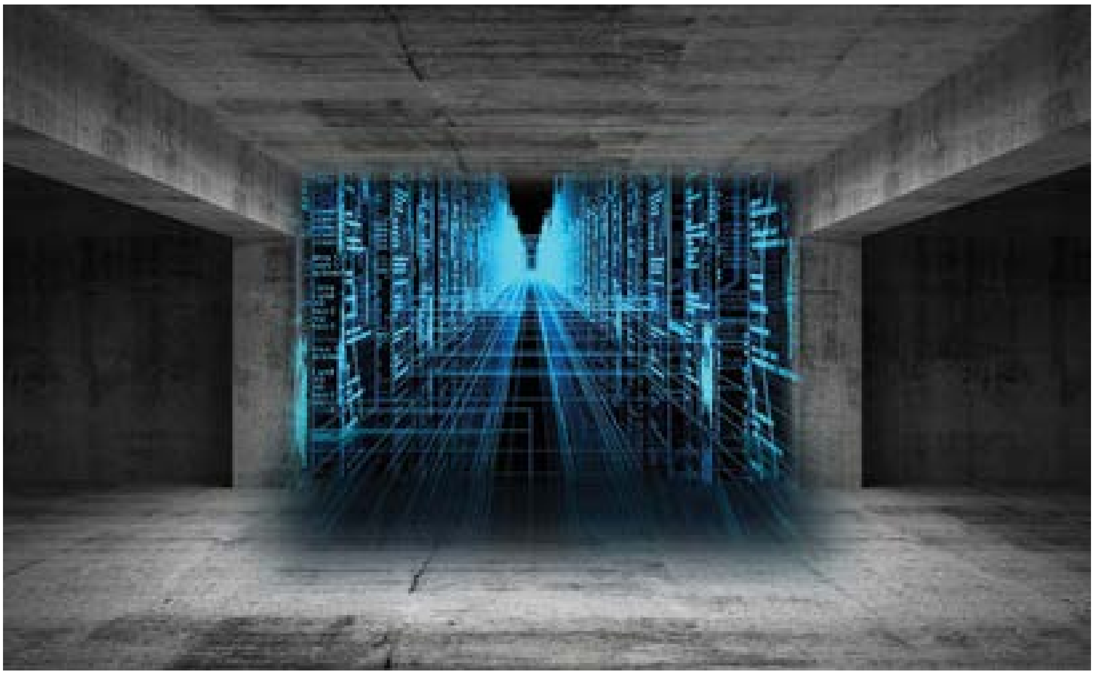
The concept of twinning, the integration and synchronisation of digital and physical objects, is a key tenet of Industry 4.0. Digital twins will enable the creation of a digital model of a product, process or system, and its virtual testing, prototyping and analysis without physical production or testing. Similar requirements for digital twins have been identified in the energy sector (Chapter 7). Some investments in 'digital twinning' have already been made by UK Research and Innovation and UKCRIC. Further work is needed to map existing capability, assess how connected it is and determine what additional infrastructure might be needed.

Theme 6: Enhancing future connected digital technologies	
How this area can be progressed/indicative approaches	
Powering future digital technologies: investment to underpin more energy-efficient ways of designing, controlling and powering new technologies	To prevent technological development being curtailed by energy costs, new technologies will need to be designed to limit energy demand, be usage-aware and adaptable, and potentially contribute to energy generation. The next step would be to work with the research and business communities to consider the options for common energy efficiency challenges across application sectors. These could then be used to identify the specific research and innovation infrastructure implications.
Developing living labs and digital twins	Learning about the intersection of autonomous vehicles, drones, smart infrastructure, robotics and smart services would benefit from the development of a family of living labs or demonstrators that can drive innovation, experimentation and learning through the delivery of working solutions to real-life problems. The next step would be to explore what the opportunities and requirements might be for infrastructure investments in 'digital twinning' across the research and innovation landscape.

CASE STUDY:
Data and Analytics Facility for National Infrastructure (DAFNI)

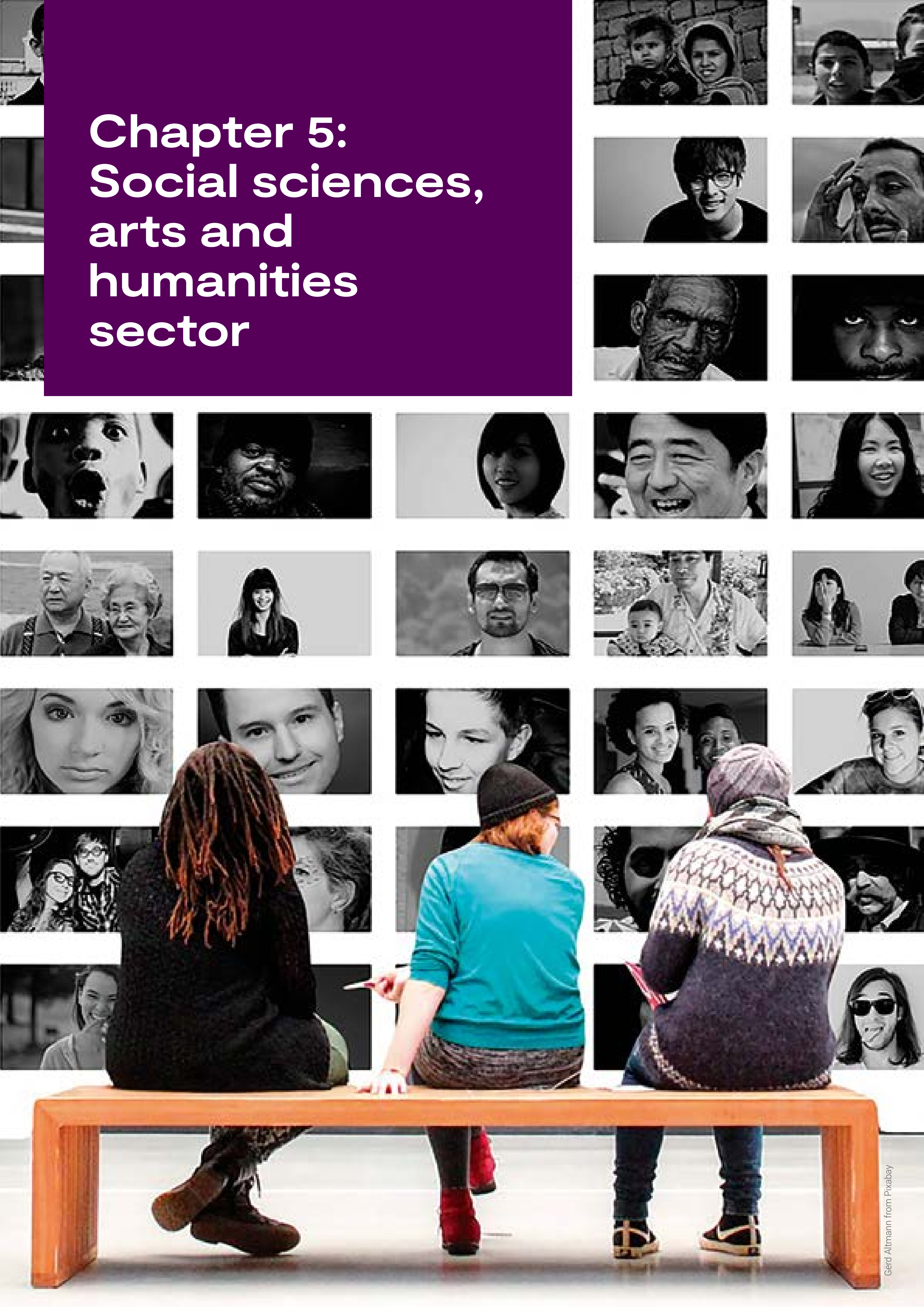
DAFNI is a facility in development, funded as part of the UKCRIC and based at STFC based at the Harwell Campus. It provides computational resources and bespoke software applications to advance the state of national infrastructure research.

'Digital twinning' is one of a number of modelling techniques that DAFNI aims to support through the standardisation of data/model sources and common access to these resources. The DAFNI facility aims to provide the interfaces and mechanics to allow integration of the first National Digital Twin as outlined within the Gemini Principles published by the Digital Framework Task Group[54].



Harri Vick from Pixabay

Chapter 5: Social sciences, arts and humanities sector



Gerd Altmann from Pixabay

Social sciences, arts and humanities are fundamental to understanding people, their interactions with the world around them and the ways in which their lives, the economy and the environment can be improved through evidence-based interventions. They provide the critical frameworks through which we can evaluate the impact of human activity and support the development of policy and practice to address the major challenges of our time. Infrastructures that support the social sciences, arts and humanities sector play a key role in ensuring the health, wealth and wellbeing of the nation, driving economic growth and creating the conditions for greater social cohesion, equality and inclusivity.

Demand for social sciences, arts and humanities research from academia, industry, government and the third sector is growing. More than 60% of UK Government departments' areas of research interest (ARIs)[55] questions are core social sciences, arts and humanities issues with a further 20% requiring significant social sciences, arts and humanities input. While all industrial sectors require an understanding of people and behaviour (as well as of materials and processes), the fact that the UK economy is now over 80% services-based makes the need for these insights all the more important. Large and complex data sets can be analysed to gain understanding of human and societal behaviours, mapping the movement of people, practices and ideas over time and space.

The value of social sciences, arts and humanities infrastructures accumulates over time. Museum collections facilitate comparative analysis through a continual process of collecting, contextualisation and research, and longitudinal studies enable increasingly complex insights as more data are added from successive sweeps. These collections and data sources make up a significant proportion of social sciences, arts and humanities infrastructures and are the sectoral equivalent of the large-scale instrumentation-based facilities found elsewhere.

UK Research and Innovation is the major source of funding for large parts of this sector. The sector, in particular the arts and humanities, also receives significant funding through non-UK Research and Innovation government funding, philanthropic sources, charities or private sector support such as through the Department for Digital, Culture, Media and Sport (DCMS). The sector includes a number of Independent Research Organisations (IROs). IROs are research organisations that are not already part of another public sector research body, but possess in-house capacity to carry out and lead research independently in their chosen field or discipline[56].

This chapter draws on inputs from a range of expert advisory groups and consultations, with representations from across academia, industry and government. It also draws on a number of earlier independent strategic reviews and recommendations, including the UK Strategy for Data Resources for Social and Economic Research 2013–2018[57], the Administrative Data Taskforce Report December 2012[58] and more recently the Longitudinal Studies Review[59].

5.1 Overview of current capability

The social sciences, arts and humanities sector comprises data collections, surveys and longitudinal studies, as well as large-scale databases and repositories which provide data and data services across the sector. This includes universities and galleries, libraries, archives and museums (GLAMs) and other heritage organisations with world-leading collections, serving tens of millions of research object requests per year. Heritage science infrastructures can act as bridges between the humanities and sciences by using scientific analysis and technological innovation to understand, manage and communicate the human story, expressed through landscape, buildings and artefacts.

There is a strong interdisciplinary focus in this sector's infrastructures with the majority (69%) of them identified in the Landscape Analysis as contributing to research and innovation in other sectors. Nearly three-quarters (72%) help shape public policy or the delivery of public services. Their influence also extends beyond the UK; 89% define their reach as international, with the majority involved in national and/or international collaboration.

Figure 12 describes the current capabilities in the sector. The analytical capabilities include models and simulations of considerable sophistication, for example economic models such as EuroMod or the National Institute of Economic and Social

Research Macroeconomic models. Heritage and archaeological sciences both demand and stimulate collaborative research in a range of precision technologies such as remote sensing and non-invasive imaging. Museums, galleries, historic sites and properties serve as incubators for immersive technologies and enable new forms of community-led, participatory research. Research and innovation clusters in the creative industries, especially audiovisual media and fashion, demonstrate the efficacy of the R&D cluster model in driving innovation and adding value. Design leads a suite of practice-based methodologies in translating research into commercial and social innovations. In recent years, these innovations have informed transformation in areas as diverse as sustainable fashion, creative education and immersive experiences, as well as public health campaigns about smoking in pregnancy, auto-enrolment in workplace pensions and place-shaping and social development through culture and heritage.

Social sciences, arts and humanities infrastructures tend to be long-lived. Some, such as the British Museum (founded in 1753), have existed for centuries others have been established in recent decades, for example the National Child Development Study which began in 1958. Such longevity brings challenges, including the need to store, maintain, preserve and make accessible expanding collections. Across all infrastructures, there is a strong focus on management and access, both physical and virtual, with researchers accessing data and services through embedded expert capability. For example, the UK Data Service provides access to major UK government-sponsored surveys, cross-national surveys, longitudinal studies, census data, international aggregate, business data and qualitative data. The Archaeological Data Service (ADS) is a world-leading digital heritage data archive driving advances in archaeology and data management. Data services work to ensure the long-term sustainability of digital archives through the design, development and trial of transformational technologies.

These infrastructures support access to data and collections through training, events, methods and tools. They play an important role in developing researchers' analytical skills to support policy-making. The sector also adds value through partnership and collaboration. For example, the Social Data Science Lab, the Consumer Data Research Centre, the Creative Industries Clusters and Audience of the Future programmes collaborate on projects with a range of businesses and government partners. Significant resources are also used to manage access to commercially sensitive, restricted or personal data, and to support creative skills and the communication of research to non-experts. Planning and support will ensure that discrete or local infrastructures can be linked to enable the maintenance of former projects and search and analysis across corpora – for example, the ReStore project, part of the National Centre for Research Methods, which preserves, sustains and actively maintains selected online research methods and resources beyond the initial funding award.

5.2 Future direction

Social sciences, arts and humanities researchers consider their collections, archives and data sets, along with the e-infrastructures required to access and unlock them, in large part to be their infrastructures. The large increase in data and information available and advances in the technologies to integrate and analyse these sources are potentially transformative – in particular:

- Expanding the capability to link and integrate data sets, which can in turn generate more multi-level models incorporating social, economic, environmental and physical (e.g. geographical and geological) data
- Improving usability of models and simulations for policy analysts for future planning and 'what if' scenario preparation, coupling these models with the research and interpretive skill-sets of social sciences, arts and humanities researchers
- Using the increased availability of real-time data streams to improve the response time, precision and accuracy of simulations and models
- Using machine learning to support analysis of very large data sets
- Growing the capability to link and integrate collections, whether of objects data or multi-modal
- Using the International Image Interoperability Framework (IIIF), which opens up new possibilities for building discovery

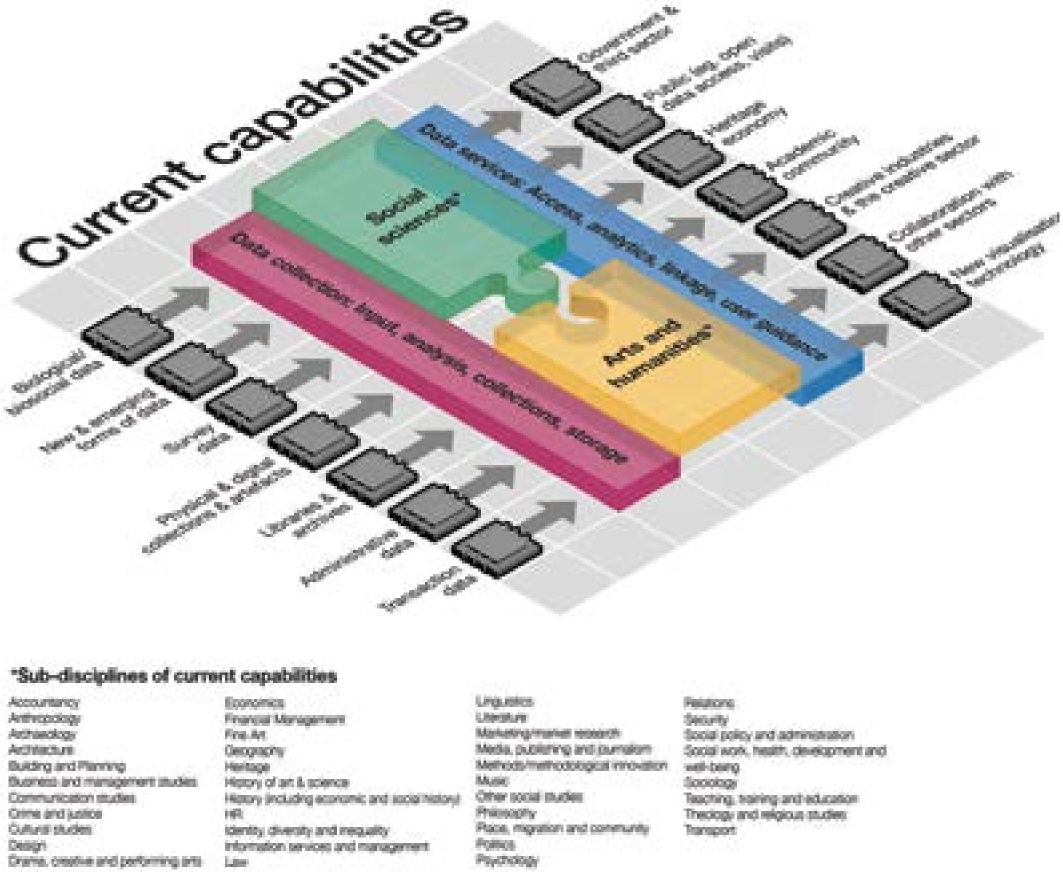


Figure 12. Current Capabilities in the social sciences, arts and humanities sector.

applications and exploring collections even without full metadata

- Public attitudes and policies are also changing and we will need to respond to public demand for transparency, privacy and informed consent

The following key themes will guide social sciences, arts and humanities infrastructure development over the coming years:

Connectivity, discoverability and interoperability: This sector has exceptional resources of data, information and collections. Collectively, these information sources represent the systematic accumulation of millennia of knowledge and practice, creating the capacity to drive innovation and to inform our understanding of major global challenges. Some are highly connected and accessible whilst others are more dispersed, making the landscape fragmented and resources hard to find. If an infrastructure, such as a website or database, is an output of a fixed-term project, it is rarely maintained as a live resource after completion and rapidly becomes undiscoverable. A key challenge for the social sciences, arts and humanities sector is to prevent time-bound infrastructures from becoming obsolete on completion of the project. Planning and support to link discrete or local infrastructures could enable better maintenance and utilisation of assets.

Appropriate and sustained investment: Integration and linkage of resources across the sector are major challenges given their complex and multi-modal nature. We currently lack tried and tested cross-disciplinary methodologies to achieve this. Enhancing discoverability and interoperability within and across disciplines will catalyse new research areas and drive cross-disciplinary working. Key areas which would benefit from greater interoperability and discoverability include creative industries and social and economic research, health research (e.g. analysis of media content for mental health research) and environmental analysis (e.g. analysis of archaeological evidence to predict topographical changes over time). Success here is dependent on appropriate and sustained investment to maintain existing capabilities and develop new infrastructures.

CASE STUDY: Research using linked administrative data enhances government help with energy efficiency

martinasky97 from Pixabay

The Welsh Government's Warm Homes Nest scheme was launched in 2011 to provide free home energy efficiency upgrades to vulnerable households[60]. The impact of the scheme was evaluated by researchers using ESRC-funded Administrative Data Research Centre to access NHS and administrative housing data. They found that individuals who were part of the scheme were significantly less likely to see their GP for respiratory illnesses or asthma events in the period following intervention, as compared to a control group[61]. As a result, eligibility for the government scheme was extended to low-income homes with people suffering from respiratory or circulatory conditions and funding for the research was extended to 2018-2021.

Curation and access: Technological developments and dependencies on permissions for secure and personal data have shifted the emphasis in social sciences, arts and humanities data infrastructures from data storage to data access. This is reinforced by the ambition to establish Open Data for research and develop FAIR data (Chapter 11). These infrastructures are evolving from being data owners to being custodians and curators of data. Curatorship implies a number of roles: provision of trusted data (in terms of provenance and ensuring ethical data management), active and expert curation of that data (in both its physical and digital formats) and provision of a conduit through which the private sector and other users can access information. Bringing together expert curatorship with integrated data access can help to realise the full potential of dispersed infrastructures and improve discoverability across the user spectrum.

Investment in technologies, such as machine learning, is needed to deliver step-changes in the ability of researchers to utilise existing large and complex data types, e.g. multimedia data. This will enable the creation of persistent identifiers for digital objects and interoperable frameworks, systems and related multimedia data automated search facilities, all of which could facilitate step-changes in visualisation technologies and user interfaces, advancing public access, communication and co-production of research.

Our consultations over the course of this programme highlighted a need for a more inclusive and future-oriented data collection and curation infrastructure. This needs to fully embrace the UK's diverse society and incorporate bodies of knowledge from other disciplines (such as human genome data) and public data curation processes (such as citizen science). New tools and models are required to manage data, to develop participatory data infrastructures and to enable the development of new modes of knowledge production and knowledge exchange.

Integrated environments: There is a need for the combination of digital connectivity with physical spaces to facilitate access, close study, incubation and experimentation. Recent investments in the Creative Industries Clusters and Audiences of the Future programmes provide an unrivalled platform on which to consolidate the UK's leading position in research on and with the creative industries. Future social sciences, arts and humanities infrastructure needs to expand this model beyond audiovisual media and fashion across the whole of the creative industries, building collaborations with other sectors including health, automotive, education and tourism.

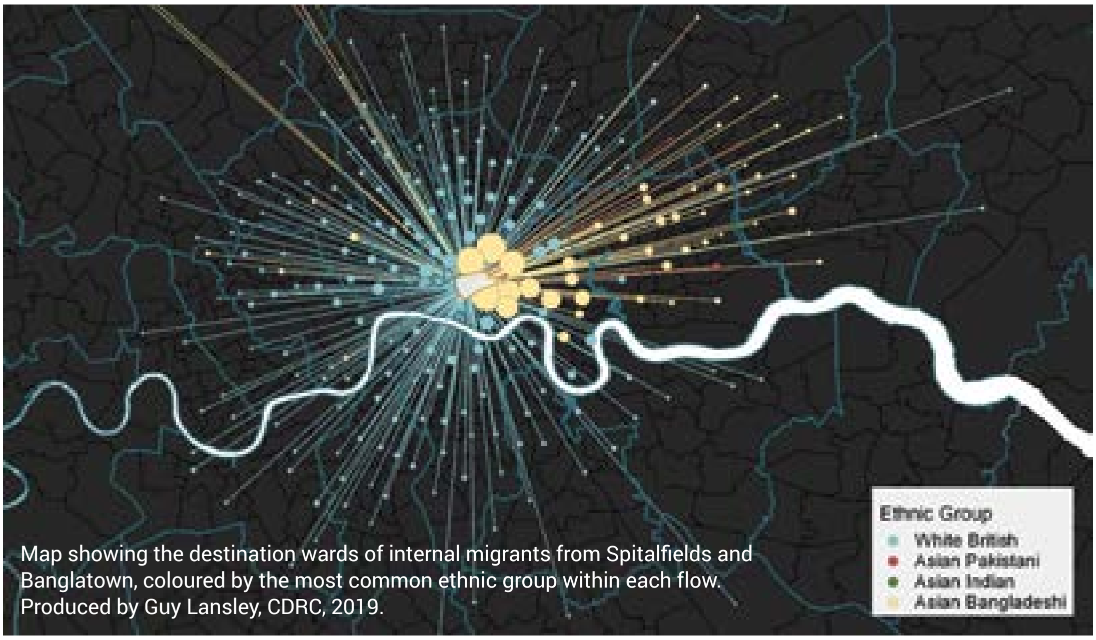
Adaptation of new technologies: There are opportunities for infrastructures to adapt new technologies, such as high-performance graphics, quantum computing, augmented reality, sensor technologies, virtual reality and hologram technology, as well as mapping and geo-referencing beyond Geographic Information Systems to open up exciting ways to collect, create, distribute and participate in products and experiences. The scale of digital facilities needed presents a formidable challenge for any single institution, making the need for a distributed and integrated network essential.

Modelling and simulation: The sheer abundance of data has transformed social sciences, arts and humanities, acting as the catalyst for the development and application of new analytics and transformative technologies to increase the accuracy and granularity of modelling and simulation. Developing these tools and techniques can lead to capabilities that serve the sector in a way that is analogous to the national supercomputers. Future infrastructure can build bridges between sectors by working towards real-time information flows and combining different forms of data with major applications in public policy, public service delivery and smart urban design.

CASE STUDY:
Linked data on individuals and households used to map Greater London's housing markets and the changing ethnic composition of neighbourhoods

The Consumer Data Research Centre (CDRC) was established by the ESRC as part of the Big Data Network. The Centre works with consumer-related organisations to make consumer data resources accessible to trusted researchers. It aims to make UK research sustainable in the future, by maximising consumer data, to support consumer-related organisations in innovating and to drive economic growth.

Researchers at the CDRC have created a Linked Consumer Register of almost all adults and households in the UK from 1997 onwards, with annual updates. This infrastructural database, comprising roughly 1 billion individual records, is held in the CDRC secure data facility and is being used to better understand the nature of social and geographical mobility across the UK. An associated CDRC collaboration with the Office for National Statistics has led to the creation of a free-to-access software tool that makes it possible to estimate the ethnic composition of communities based upon lists of given and family names. Together, these software and data resources are being used by the Greater London Authority to identify London's 'escalator' housing markets (areas in which gentrification and associated house price inflation provide stepping stones for individuals to move on to better areas) and patterns of associated changes in the ethnic composition of neighbourhoods. Elsewhere, in Blackburn, this database is being used to understand the challenges of neighbourhood segregation in one of the UK government's Integration Areas. More generally, the database makes it possible to chart population changes, internal migration patterns and social mobility outcomes across the UK, at scales from the local to the national. The quality of the linked data infrastructure is documented in the peer-reviewed literature and aggregate anonymised or pseudonymised extracts are available upon successful application to the CDRC Safeguarded and Secure services.



Map showing the destination wards of internal migrants from Spitalfields and Banglatown, coloured by the most common ethnic group within each flow. Produced by Guy Lansley, CDRC, 2019.

5.3 Future requirements and opportunities

Our vision for the future of social sciences, arts and humanities infrastructures has been driven by community engagement, the Arts and Humanities Research Council (AHRC) and Economic and Social Research Council (ESRC) Delivery Plans[33] and other key strategic reviews such as the Longitudinal Studies Review[59]. Since the publication of the Progress Report we have undertaken further community engagement to validate and develop the content of this chapter. Within each of the themes below, we present some potential opportunities for future infrastructure capability across the whole UK landscape.

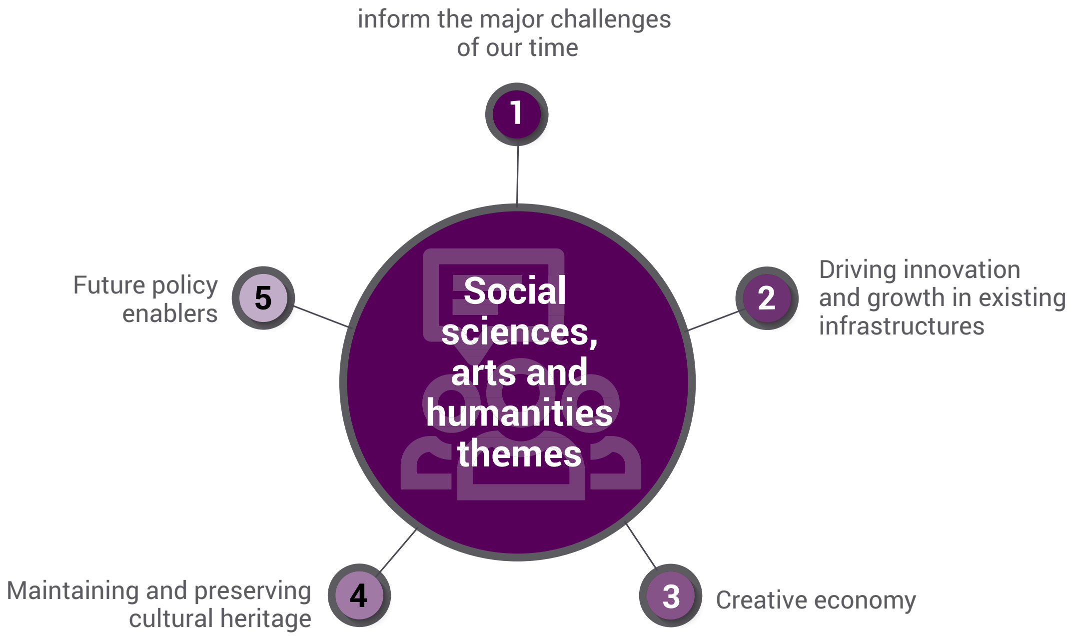


Figure 13. Social sciences, arts and humanities themes overview.

Theme 1: New data infrastructures to inform the major challenges of our time

The major challenges of our time, from the Industrial Strategy Grand Challenges of Ageing Society and Clean Growth to social cohesion and productivity, are mainly caused by, differentially affect and require solutions that involve people. This requires an evidence-based understanding of individuals, communities, groups and populations, and will require a broad range of data including: administrative data (gathered by government and other public bodies from public services and other interactions), transaction data (including consumer data and transport usage), longitudinal data (providing evidence of the causal impacts of social and environmental contexts on people's choices, behaviours and outcomes in later life) and human behaviour data. Maximising the potential value of this data, some of which is sensitive or personal, requires careful data management, contextual knowledge and complex linkages and analyses, as well as robust mechanisms for tracking usage and impact.

Theme 1: New data infrastructures to inform the major challenges of our time

Subtheme: Health and wellbeing of populations

New capabilities would address gaps in the current portfolio, add value by connecting and supporting existing capabilities in this area and provide additional support to users. Infrastructure investments here will complement those in the 'population data for health research' theme in the biological sciences, health and food sector (Chapter 3) with opportunities to work jointly to support underpinning areas, e.g. around the co-development of technologies, methods and tools, establishing best practice, or complementarity of approaches.

How this area can be progressed/indicative approaches

Population research resource	Infrastructure to allow researchers across disciplines to access data from cohort/longitudinal studies, improving usability and discoverability and maximising value from existing investments in longitudinal studies. A major role for new infrastructure would be to track both the use and the impact of such studies.
New birth cohort	The UK's current longitudinal studies have a global reputation, but there is a significant and growing evidence gap stemming from the fact that the members of its youngest cohort study, who were born at the turn of the century, have now reached early adulthood. Scoping work is under way to explore the most effective way of designing the next birth cohort, as are plans for additional data collection from the Millennium Cohort Study, to focus on the transition from childhood to adulthood. This gap was highlighted by the MRC Strategic Review of Cohorts and a new study was recommended as part of the Longitudinal Studies Review. This approach would be closely aligned to the biological sciences, health and food sector aim to develop a new adolescent cohort.
Developing long-term, sustainable investment in life course and population research	There are opportunities to build on decades of investment in the UK's unique portfolio of cohorts, hosted by the Centre for Longitudinal Studies, which would provide the data required for interdisciplinary research to understand and tackle major complex challenges facing the UK economy, including: ■ Development and delivery of next-generation cohort design and methodology ■ Fostering international collaboration with a worldwide network of cohort initiatives This would develop and use novel data collection technologies (behavioural and biomedical data) to capture data on key life transitions.
Understanding intergenerational change across cohorts	A series of scoping activities are needed to understand intergenerational change across cohorts, by enhancing and utilising administrative data linkage. This was a core recommendation of the Longitudinal Studies Review.

Subtheme: Economics, productivity and growth

With UK productivity well below that of peer nations, and with an associated lag in wage growth, understanding and stimulating productivity is arguably the UK's biggest economic and social problem. Business and consumer data are vital for understanding economic and productivity challenges. As with administrative data, these data types are not generated for research and need to be carefully managed and prepared to be usable for this purpose. Once data are available, powerful analytic approaches can be brought to bear to generate important and meaningful insights. Addressing regional inequalities, skills shortages and changing labour markets is crucial to productivity and sustainable, inclusive growth.

How this area can be progressed/indicative approaches

Productivity research resource	A UK Research and Innovation productivity research resource or institute would provide a systematic understanding of what effective action is required to address the UK productivity challenge, one of the biggest challenges facing the nation. This would enable the collection, linkage and analysis of data that supports the institute's lab-based research environment.
Data linking within and across firms	Enhanced capability to link individual firm-level data and employee-employer data would facilitate research into the determinants of productivity, including the role of human capital.

Subtheme: Boosting social cohesion – understanding values, attitudes and behaviour

Longitudinal studies, such as Understanding Society: the UK Household Longitudinal Study, are core social science data infrastructures. These surveys involve tracking and gathering information from groups of individuals or households over time to create a clearer picture of society. They increase in value over time as new waves of information about their participants' lives are added to what is already known about them. This enables a deeper understanding of people's changing lives and attitudes and informs the development of robust evidence-based policy interventions designed to address social issues and lead to improvements in people's lives. These studies are complemented by cross-sectional surveys (which interview fresh samples of people on each occasion) and gather information on social and political attitudes to build a comprehensive understanding of attitudes and behaviour. Supporting new phases of activity and enhancing existing approaches by, for example, incorporating the capacity to access and link survey data to other forms of data and use of advanced analytical tools would drive a step-change in capability.

How this area can be progressed/indicative approaches

Global social comparisons	A new global social survey resource would enable access to internationally comparable social surveys, allowing high-level comparative analysis and the sharing of data across international boundaries. The detailed composition of the infrastructure would be subject to a scoping exercise. This would move above and beyond existing surveys in the landscape by playing a role in bringing surveys together in a way in which they are comparable (harmonisation) and by being methodologically and geographically more ambitious.
Qualitative longitudinal study	Scope the potential for ground-breaking new qualitative data collection to complement longitudinal quantitative analysis in consultation with the community. This would set new standards for how studies could be integrated and would require innovation in machine learning and image analysis. This would be applicable and add value across quantitative longitudinal studies.

How this area can be progressed/indicative approaches *cont.*	
Understanding Society waves thirteen to fifteen	The next phase of investment (waves thirteen to fifteen) would capitalise on the most effective opportunities for innovative multi- and interdisciplinary scientific and policy-relevant research by exploiting new and emerging technologies in data collection methods and linkage. It would create unique opportunities for interdisciplinary research to improve human health by continuing to build and develop a cutting-edge resource, combining biological and social data over time.
Globally networked election studies	Building on the benchmark British Election Study would enhance and add richness to the existing information by drawing on global election studies to understand how different societal influences and attitudes translate into behaviours at elections. This project is currently being scoped.
Young Lives	The next phase of investment in the Young Lives longitudinal programme would build on methodological learning from the original multi-country longitudinal programme and deliver the data in a number of formats, to support a range of audiences (academics, funders, data managers, research managers).

CASE STUDY:
UK birth cohort studies inform guidance on prevention of binge drinking

Researchers Dr Barbara Jefferis, Professor Chris Power and Professor Orly Manor used data from the 1958 National Child Development Study and the 1970 British Cohort Study to investigate the adult consequences of early drinking patterns among teenagers and those in their early twenties. They found that binge drinking was common among British adults and that drinking levels in adolescence were significantly associated with problem alcohol use in subsequent decades.

Their findings highlighted the importance of preventing and identifying alcohol problems as early as possible to prevent health and social concerns in later life. This was crucial information at a time of rising concern about the levels of binge drinking and its societal consequences. They produced a report for the Cabinet Office's Strategy Unit[62] and were cited in numerous Health Committee reports. This has gone on to influence the government's Alcohol Strategy for England in 2012-13[63] and public health guidance including the National Institute for Health and Care Excellence (NICE) guidelines on Alcohol-use disorders and prevention[64], and Draft Guidance on the Consumption of Alcohol by Children and Young People from the Chief Medical Officers of England, Wales and Northern Ireland[65].

LEEROY Agency from Pixabay

Theme 2: Driving innovation and growth in existing infrastructures

Addressing regional inequalities, skills shortages and changing labour markets is crucial to productivity and sustainable and inclusive growth. We can harness existing administrative data to complement and add value to existing (and planned) human and societal data sets exploring these issues. There is significant potential to drive a step-change in our existing infrastructure capability, addressing consumer and business data, multilingualism, health and human behaviour and their influences on society and the environment. Many of the ideas set out in the tables are relevant across multiple themes.

Theme 2: Driving innovation and growth in existing infrastructures	
Subtheme: Transforming administrative data access and maximising use	
There is a wealth of administrative data held in government departments and other public bodies with enormous research potential, but access and use present significant challenges. This data has not been developed with research in mind and needs expert curation, linkage and access requirements brokered with data holders.	
How this area can be progressed/indicative approaches	
Administrative Data Research UK Phase II	The next phase of the newly inaugurated Administrative Data Research UK (ADR UK) would link administrative data to support research into income, working patterns, travel patterns, education, health and criminal history for all who come into contact with government departments and public services.
A 'administrative data spine' for longitudinal studies	The Longitudinal Studies Review recommended the development of a benchmarking 'administrative data spine' of population identifiers with maximum coverage of the UK population. This would address a number of pressing strategic priorities in the development and use of longitudinal studies including: providing a sampling frame for potential new studies; enabling assessment of the representativeness and inclusion of existing longitudinal studies and other data sets providing a means to address bias in these data sets; and facilitating linkage of administrative data to longitudinal survey data for research purposes. The detailed approach and features would need to be scoped. There is also an opportunity to expand use across disciplines to add value to population studies within the biological sciences, health and food sector.

Subtheme: Analysis and research centres in consumer and business data

Business and consumer data are vital for understanding economic and productivity challenges. As with administrative data, these data types are not generated for research purposes and the data needs to be carefully managed and prepared for it to be usable for research. Once data are available, powerful analytic approaches can be employed to generate important and meaningful insights.

Current infrastructures focus on the needs and socio-economic factors that affect the prosperity and wellbeing of citizens in local communities in an era of global change. Programmes of work include fundamental and applied research and an extensive integrated knowledge exchange and training programme.

How this area can be progressed/indicative approaches

'Big data' innovations: growing the business and local government data research centres	Creation of a national-level demonstrator using the development and application of AI and data-sharing techniques would significantly extend existing data infrastructures and their service offer. It could enable them to design and host a platform to: ▪ Develop, experiment with and apply advanced AI techniques ▪ Plug-in primary or secondary/derived data sets from their partners to present in near-real-time the outcomes of research and the application of AI and analytics

Subtheme: The future of data access and analysis

Today's world is increasingly connected and digital, where new forms of data are generated via a multitude of channels and devices on a second-by-second basis. These channels and devices include: hardware (such as smartphones, tablets and other devices); software (such as social media, videogames and digital art); and the data that is produced from user interactions. Changes in practices and technologies are influencing how we think about data access – users may be much less interested in how and where data are held and much more concerned with how to access the data.

This challenge applies to a wide range of social sciences, arts and humanities disciplines, including the heritage sector which has identified the need for frameworks and information management systems that can facilitate the collection, preservation, analysis and interpretation of this rapid increase in 'born-digital' objects.

Another challenge is preventing infrastructures from becoming obsolete if they are no longer directly supported – if an infrastructure, such as a website or database, is an output of a fixed-term project it is rarely maintained as a live resource after completion, rapidly becoming undiscoverable. Infrastructure that enables the capture and analysis of this material will enhance our understanding of the ways in which digital technologies impact lives and our capacity to inform and influence the future direction.

How this area can be progressed/indicative approaches

Centre for new and emerging forms of data	Consideration given to how to address the challenges around access, creation and analysis of new and emerging forms of data, for instance through scoping for a new infrastructure focused on new data. This could involve a range of methodologies, such as AI, spatial analysis, geostatistics and a wide variety of other disciplinary perspectives, to address potential research questions on social processes and human behaviour, for example; ▪ Population dynamics and societal change – migration, ageing populations, population growth and welfare/well-being

How this area can be progressed/indicative approaches *cont.*

	■ Public health risks – spread of communicable diseases, lifestyle factors and non-communicable diseases ■ Economic growth, innovation, research and development activity – science, education, workforce of the future, global trade and financial stability ■ Social and environmental vulnerability and resilience – environmental change, dynamics of poverty and related policy evaluations
Next-generation data services: archives of the future	The UK Data Service (UKDS) is a flagship data infrastructure for the social sciences. The next phase in the development of this service would provide access to an even greater variety of data sources, for an even greater number of users. Building upon developments in recent years, including the International Data Access Network, the future service would be able to provide secure access to international data sets and be responsive to changing security standards of the provision of sensitive (individual-level) data. This future data service will need to be flexible to meet the changing demands of its stakeholders (notably data owners/controllers and researchers).
Maintaining methodological excellence in the social sciences	The National Centre for Research Methods was commissioned to promote a step-change in the quality and range of methodological skills and techniques used by the social science community. The next phase of development would enable us to deepen the interdisciplinary and non-academic reach of the centre. It would focus on widening the user base outside of the social sciences to researchers working in the private, public and civil society sectors, putting the development of new networks and partnerships at the heart of the activity.
New investment to sustain live online digital content	Development of a UK-wide network of sustainable trusted repositories for digital data, integrated into the academic research community and supported by the promotion of digital skills and community engagement, would significantly enhance future discoverability and use. Including capability to select, sustain and archive live online digital content from past and future research and supporting greater interoperability would ensure that the outcomes of individual projects are preserved, adding greater collective value.

Subtheme: Digital humanities and its future (technologies, methodologies and skills)

Digital humanities is a rapidly evolving field that applies Information and Communication Technologies (ICT) to preserve digital artefacts, making them more accessible to users and enabling analysis and mining of data in new and previously impossible ways. It supports the creation of more socially embedded and responsive technologies that are able to balance the needs of researchers, industry, the third sector and the public. It also facilitates the exploration and analysis of large-scale historical and cultural data sets and enables new ways of sharing and visualising the data.

How this area can be progressed/indicative approaches

Technologies and methodologies for digital humanities, advanced data visualisation and curation	Significant opportunities exist to aggregate, describe and analyse digitised material. Establishing centres of excellence for the development of new technologies, frameworks and methodologies for collection, archiving, analysis and interpretation would bring existing digital humanities and social science techniques together with techniques such as AI and machine learning. This would open up experimentation with: immersive data visualisation techniques and blockchain technologies, digital reconstruction and visual modelling; mapping/geo-referencing; remote data-sharing and inquiry, scanning and 3D laser scanning; 3D printing technologies; and remote-sensing and drone technologies.

Subtheme: Research in languages and multilingualism

Although our world is increasingly mobile and interconnected, fundamental problems of translation of languages and cultures inhibit communication and the effectiveness of policy interventions both domestically and overseas. Investment in multilingualism research, machine translation and corpus research (computational analysis of language and discourse) will enrich the evidence base for policy intervention and facilitate more effective implementation.

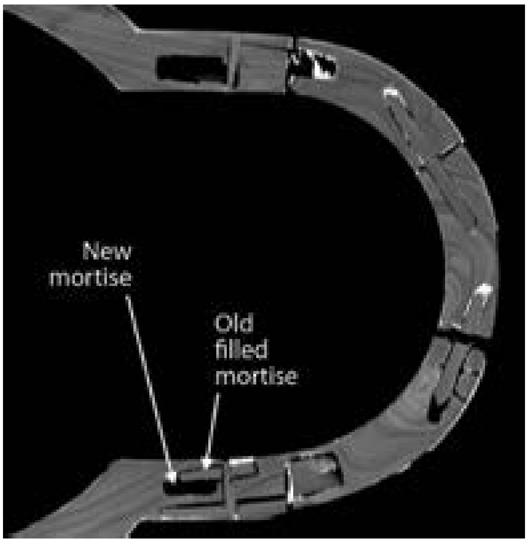
How this area can be progressed/indicative approaches

Modern languages policy and evidence centre	A new policy and evidence centre for the modern languages would provide an important underpinning resource for researchers, policy-makers and practitioners to better understand the multilingual make-up of the UK and the significance of language to policy and practice in areas such as social cohesion, security, trade and overseas development.
Machine translation facility	Infrastructure (hardware and software) to support use of AI and machine learning would support the translation of texts and ensure digital equality in an area dominated by private corporations.
Common languages resource infrastructure	Consider options to take forward infrastructure that would support the recording, analysis and investigation of the structure and function of languages, developing large corpora and linking them together.

CASE STUDY:
New insights into ancient Egyptian coffins

Since 2014, the Fitzwilliam Museum in Cambridge has been conducting cutting-edge interdisciplinary research into its collection of more than 200 ancient Egyptian coffins and coffin fragments. Bringing together a team comprising of Egyptologists, conservators, a pigment analyst, an expert in historical painting techniques, an ancient woodworking specialist and a consultant radiologist, alongside the application of advanced imaging techniques such as Computed Tomography (CT) scanning and X-radiography, has generated new insights into the coffins' construction and the history of the coffins and their owners[66].

CT scanning of the inside of Nespawershefyt's coffin, in collaboration with the Department of Radiology at Cambridge University Hospitals NHS Foundation Trust and the Medical Imaging Group in the University's Department of Engineering, revealed a hotch-potch of new and reused wood, redundant joints and remnants of another closure mechanism under the rich decoration. Detailed analysis of scan data using software developed originally for 3D medical ultrasound helped the team understand how large parts of a much earlier coffin lid and box had been recut, refashioned and reused in the creation of Nespawershefyt's coffin.



Coffin set of Nespawershefyt (mummy board, inner coffin, outer coffin).

Developing our understanding of reuse adds to and refines the significant quantifiable data that can be derived from the study of these objects. This has led to new interpretation of ancient economics, social situations and craft specialisation over thousands of years. Through investigating the reuse of coffins, the team is able to develop new interpretations of the function of coffins within funerary rituals and the processes of burial in ancient Egypt and improving our understanding of the materiality of tomb robbery.

Subtheme: Assessing societal attitudes and behaviours on the environment

Climate change and unequal access to health, wealth, education and resources are two of the most pressing, long-term global challenges. The UK government has taken a leading role in this area through its Clean Growth Strategy and Defra's twenty-five-year plan for the environment.

Research at the individual, cultural, political and corporate level is central to the successful implementation of the social, structural and systemic changes required to change attitudes and behaviours. Social sciences, arts and humanities infrastructures have the potential to: help us better understand these issues; find, evaluate and implement solutions; inform better choices; and increase societal resilience.

How this area can be progressed/indicative approaches

Changes in behaviour, e.g. around the environment	Scope the potential for existing social sciences, arts and humanities infrastructures which hold relevant data to develop data linkages with other data sets of interest or develop new access and analytical mechanisms to understand and integrate this data.
Global Biodiversity Information Facility	The Global Biodiversity Information Facility is an international open access facility that provides an important evidence base on biodiversity to inform sustainable development. There are opportunities for new infrastructure which would incorporate the UK's botanical, zoological, palaeontological and geological collections data.
Environmental and geo-archaeological databases	Creation of fully digitalised and interoperable archives of geo-archaeological data would enhance our ability to reconstruct and understand past environments and climate.

Theme 3: Creative economy

The creative industries are an undoubted strength of the UK economy, accounting for £92 billion of Gross Value Added (GVA) 2 million jobs and are growing twice as fast as the economy as a whole. This potential was recognised by the government in the Industrial Strategy, prioritising an early Sector Deal[67]. The ISCF-funded Creative Industries Clusters programme demonstrates the potential for adding future economic value through geographic and sectorally focused creative clusters. There are opportunities to build on this to initiate a world-leading creative economy R&D programme in disruptive areas where creative research can provide significant added value to other sectors of the economy.

The design sector contributes 7.2% of the UK industries' GVA to the economy[68] and the GLAM sectors draw on their collections to drive innovation in key areas of the creative industries. For example, the Business of Fashion Textile and Technology Collaborative Research and Development Cluster, funded through the Creative Industries Cluster programme, is working in partnership with the V&A to test new and existing synthetic and natural materials for new product development.

While recent emphasis in cultural and design research has been on the digital environment, this needs to be balanced against a need to maintain an understanding of the physical world and the knowledge that working with physical objects can bring. Familiarity with both physical and digital can also lead to development of new experiences creating new, blended products and experiences that integrate the material with the digital environment. For example, a student on the AHRC's Collaborative Doctoral Partnerships programme uses her knowledge of embroidery and digital fabrication to 'repair' and reconstruct sixteenth century embroidered garments in the advanced stages of deterioration. The technique breathes new life into fragile objects that would otherwise remain hidden from the public and drives innovation in the emerging field of e-textiles. Investment in innovative spaces and research environments allows users to access research objects and in-house expertise to incubate and test new research methods, technologies and ideas.

CASE STUDY:
Dinosaurs and robots: test beds for immersive technologies

Advances in virtual reality and augmented reality help create experiences that can bring science to life. The Creative Industries Clusters and Audience of the Future programmes are supporting a series of immersive experiences that allow audiences to experience museums in new ways.

Dinosaurs and Robots, an Audience of the Future demonstrator project, combines mixed reality technology and immersive theatre with new academic audience analysis to transform the traditional static museum experience into a rich encounter where objects come to life. Creative co-directors, the Almeida Theatre and immersive content studio Factory 42, will create two mixed reality visitor experiences supported by scientists and curators from the Natural History Museum and the Science Museum Group. At the Natural History Museum, visitors will 'meet' and 'interact' with a digital cast of dinosaurs. At the Science Museum, it will be robots and artificial intelligences. Visitors will be immersed in a multisensory, experiential environment where they can shape their own narratives and experience the work of scientists and palaeontologists.

Researchers at the University of Exeter, co-funded by Sky and the UK arm of US spatial computing firm Magic Leap, are measuring the impact on audiences to inform the design of future exhibits. They are using novel data retrieval methods relating to: eye tracking and biometrics; identification of psychological antecedents for positive visitor experiences using mixed reality and objective physiological indicators; and identification of physiological markers to improve experience design and personalisation.

Factory 42

Theme 3: Creative economy

Subtheme: Creation of spaces in which innovation can take place

Technologically enabled spaces are essential to the growth of innovation and design in the creative industries and ensure a pipeline of technological innovation. The heritage sector offers unique, interdisciplinary environments in which industry, creative practitioners and researchers can collaborate to develop and test technologies for new audience experiences. Such spaces facilitate the development of new paradigms for multi-modal, participatory research and the public spaces offer opportunities for prototyping new, blended audience experiences.

How this area can be progressed/indicative approaches

Evidence base for early-years pedagogies and skills	Establishing a national centre for play, creativity and skills would provide the physical space and expertise to develop and test early-years pedagogies and build creative confidence through play and interaction – both physical and digital – with materials, objects and crafts. This could evidence and measure the value of acquiring hand-eye skills at an early age with a strong focus on transferability and 'skilling for the future'.
New investment in technologically enabled spaces to incubate new technologies and enable interdisciplinary research	The creation of blended study facilities embedded in heritage institutions and storage facilities would enable researchers, designers and creative practitioners to access physical collections, digitised holdings and complex, born-digital objects such as videogames and interactive digital novels. Such infrastructures could facilitate interdisciplinary scholarship, offering opportunities to develop AI and new visualisation techniques. They would also create an environment in which the creative industries, heritage sector and academia can collaborate to develop, prototype and user-test next-generation immersive products and experiences.
New investment in sustainable fashion technologies	Study, research and analytical facilities co-located with collections and expertise would enable the development of sustainable fibres and textiles for the fashion industry and prototype their production. This would incorporate spaces for interdisciplinary and collections-led research.
Investment for facilities to support design and practice-based research	Integrated technology facilities for innovative design and practice-based research would support the creative economy, providing access to materials, including music, visual arts and performing arts.
Life-size virtual reality interactivity	Establishing national capability to enable creation and exploration of digital environments would allow a different kind of virtual reality and would create the context in which new kinds of research will be conceptualised. This would enable interactive research with life-size digital environments such aquaria, wildlife locations, geological, archaeological and historical sites, museums etc.

Figure 14. Components of blended spaces environments.

Subtheme: Infrastructure to preserve data and resources for R&D in the creative industries

Access to systematically collected and documented digital artefacts such as videogames, interactive novels and social media platforms is critical for research and industry-led innovation. National infrastructure to preserve and enable access to otherwise obsolete versions and formats, as well as spaces for experimentation and product development, has the potential to enhance the UK's global competitiveness in a rapidly evolving market[69].

How this area can be progressed/indicative approaches

National creative industries research network	A national capability would enable the archiving, curation and reuse of data and other outputs (physical and digital) from the Creative Industries Clusters programme and wider Creative Economy programme.
Repository of born-digital artefacts and resources	A national infrastructure would preserve born-digital materials and data, e.g. interactive novels, videogames, social media and digital art, and capture evolving versions and the interactive content for reference and research.
Longitudinal data and policy and evidence centre	There is currently a paucity of timely, detailed and longitudinal quantitative evidence to inform policy design in the creative industries. This could be addressed by building on the Creative Industries Cluster Policy and Evidence Centre to create a longitudinal data repository for novel, local and timely data on the positions, dynamics and evolution of the UK's creative industries and its clusters.

Theme 4: Maintaining and preserving cultural heritage

The national GVA of the heritage economy is estimated at £29 billion, with heritage tourism expenditure contributing nearly £17 billion in 2017[70]. Social benefits, including improvements to mental health and wellbeing derived from engagement with heritage and a sense of connection to place, are increasingly apparent[71]. Research from Age UK reveals that creative and cultural participation is the greatest contributor to wellbeing in older age[72].

Social cohesion can be built through engagement with heritage but needs to be supported through infrastructures that recognise and reflect the diversity of today's society[73]. These infrastructures enable research that allows groups across society to discover their own identity, diverse cultural forms and heritage. This can empower them to address social challenges such as reconciliation and reparation in the wake of conflict, modern slavery or mental health and wellbeing.

The success of the heritage sector is dependent on research because of its role in identification, preservation, interpretation and public communication of heritage assets. The UK heritage infrastructure encompasses tangible, intangible and digital heritages, in museums, galleries, libraries, archives, Higher Education Institutions (HEIs) and historic environments, and a range of global collections and collaborations. Infrastructure would support sectoral needs identified in the Strategic Framework for Heritage Science in the UK 2018–2023[74], led by the National Heritage Science Forum.

Theme 4: Maintaining and preserving cultural heritage

Subtheme: Digitisation and interoperability

Digitisation of the entirety of publicly funded collections is not currently feasible. However, investment in preliminary scoping activities could establish the basis for progress towards a more fully integrated and interoperable data infrastructure with the capability to search across collections. Digitised collections across different media (archives, large objects and buildings, books, manuscripts, 2D and 3D art, digital collections and design processes and other time-based media), will enable 'big data' studies of, for example, societal trends, infectious disease or transmission of skills through time and space. Storage of visual and audio data will require a step-change in capability in terms of multimedia data-automated search facilities and visualisation technologies.

How this area can be progressed/indicative approaches

National aggregator for existing collections	Building a new digital repository or 'aggregator' would enable connectivity between museum collections data (and metadata about digital assets) already online but currently siloed. It could allow UK museums to aggregate their data to international platforms such as Europeana[75]. The aggregator will need to incorporate proven data-gathering methods and the flexibility to embrace emerging technologies.
Phased cataloguing, digitisation and connecting of national collections	Digitisation of collections held by publicly funded bodies and integration through an interoperable system would have a transformative impact on research. The scale of the undertaking means that feasibility needs careful assessment through a phased series of scoping projects on specific themes. These could range across different collections and address specific research questions in their own right.
Creation of a digital archive for the second half of the twentieth century	Creation of a new sector-wide linked data environment for twentieth century text and audio-visual collections would constitute a unique, open access international digital research resource. This could include, for example, the cataloguing, scanning, digitisation and optical character recognition of the 13 to 14 million pages of transcripts of translated BBC monitoring broadcasts from approximately sixty countries between 1939 and 1989.

How this area can be progressed/indicative approaches *cont.*

Understanding the heritage of empire and colonialism	Creation of integrated, digital resources from world and colonial collections, as well as related Black and Minority Ethnic archives, would enable research on and critical approaches to policy on race, equality and inclusion.
Video and sound search facility	The development of infrastructure with the ability to search for objects and features within audio and image files would be needed to underpin full exploitation of the above opportunities.

Subtheme: Physical storage, conservation and access

Despite the growing importance of digitisation to the research infrastructures of the heritage sector, digital proxies cannot replace originals. Adequate facilities for storage, conservation and analysis of artefacts are needed which also facilitate skills training and public access. Physical and digital collections continue to grow and appropriate infrastructure is needed to accommodate not only current collections but also those of the future.

How this area can be progressed/indicative approaches

Conservation, heritage and archaeological science research facilities	Conservation and heritage science facilities would provide physical spaces for bringing practitioners, curators and scientists together to co-design interdisciplinary, multi-modal research projects and develop skills training in conservation and heritage science. These could be embedded within or close to collecting institutions, historic sites and properties, and facilities to develop site- or collection-specific techniques, technologies, instruments and expertise. They could also develop participatory models of research and engagement to facilitate citizen heritage science approaches and generate income through the heritage economy.
UK Research Infrastructure for Heritage Science (UK-RIHS)	The European Research Infrastructure for Heritage Science (E-RIHS) is a distributed heritage science infrastructure offering integrated access to cutting-edge facilities and expertise, as well as shared data resources. Establishing a UK node (UK-RIHS) would allow a transformation of the UK interdisciplinary heritage science landscape through access to these valuable resources.
Advanced storage facilities for museum collections	Phased creation of a distributed network of advanced physical and digital facilities would transform access to and search and discovery capability for national collections. It would also provide world-class storage facilities for an ever-increasing volume of vulnerable material.

Theme 5: Future policy enablers

Future public services and policy will be shaped by a series of challenges, including but not limited to an ageing population, budgetary pressures, adoption of new technologies and administrative uncertainty surrounding the UK exiting the EU. Many of these challenges require complex multi-partner solutions and it is vital that these are based on robust evidence. To ensure that innovations in policy and practice are able to increase efficiency and effectiveness, researchers need to be able to access appropriate types of data in timely and safe ways. Data provides the evidence base for addressing these problems, but design is the key mechanism, translating research into commercial and social innovation. The challenges facing public services can be met through the process of inclusive design whereby designers ensure that their products, environments and services address the needs of the widest possible audience and through an infrastructure that bridges the gap between design and technological development and innovation.

New and emerging forms of data from smart and connected devices allow an almost continuous stream of data to be analysed; new data analytics, including AI and machine learning, offer the capacity to analyse it. This will see research that previously described public and behavioural responses to events or policy improving in both response time and granularity. Infrastructures have a powerful role in enabling this, by providing access to data, tools and expertise in both analysis and interpretation.

Theme 5: Future policy enablers

Next-generation public services are a key strategic research theme, highlighted in ESRC's Delivery Plan[33]. Providing evidence bases for policy and practice will underpin our ambitions in this area. Infrastructures that support researchers in the creation of innovative design solutions for the delivery of public services will be essential in ensuring that innovations in policy and practice are implemented effectively.

How this area can be progressed/indicative approaches	
Data for policy innovation	Provision of and access to data to underpin innovative policy making could be radically improved. Scoping is needed to identify how best to deliver this, for example as a centralised activity or distributed set of capabilities within existing infrastructures and services.
Civil society data partnership	Development of new data-sharing infrastructures and interfaces as partnerships across civil society organisations, such as Non-Profit Organisations (NPOs) and Non-Governmental Organisations (NGOs), would enhance understanding of the voluntary sector and its role in contemporary society. This would focus on transforming sharing of and access to data, increasing efficiency and maximising resources.
Design for public services	Creation of interdisciplinary innovation labs would support the application of service design as a key driver of service innovation, social innovation and user-centred innovation. Such labs could provide the space to engage in co-design with users or members of the public and foster collaboration through interaction, dialogue and development activities.
Future observatory: national centre for design and the Industrial Strategy	There are opportunities to explore the impact of design on business, people and their behaviours and to use design to support translation of research, developing prototypes and seeking commercial partnerships to allow scale-up for commercial and social benefit. This could be realised through a number of regionally located design research and innovation centres focused on Industrial Strategy Grand Challenges.

Chapter 6: Environment sector

Innovative infrastructures for environmental science enable clean growth in harmony with our environment, balancing economic and environmental gains and costs. This chapter sets out the drivers, ambitions and step-changes in infrastructure capability planned to keep the UK at the forefront of environmental science, enabling the strongest possible contribution to national and international agenda to find solutions to unprecedented environmental challenges.

Environmental researchers study the entire planet, from the deep oceans and centre of the Earth to the edge of the atmosphere and hostile environments of the polar regions. The sector has a strong track record of discoveries that bring about action, from identifying the hole in the ozone layer to the observations and models revealing the risks of climate change. Sustaining planetary health depends on our ability to understand how and why our environment is changing and to predict how it may evolve in the future.

Rising to the cutting-edge science challenges of our time and delivering environmental, economic and social solutions to real-world problems demands world-leading infrastructure. To tackle complex problems and drive scientific progress, we must facilitate whole-system approaches that ensure the UK environmental sector leads the world in research and innovation spanning scientific disciplines and borders. This must be in tandem with providing the tools for researchers, industry and other partners to move to increasingly sustainable ways of conducting research and innovation through next-generation infrastructures.

UK Research and Innovation provides a platform to deliver shared outcomes from the environment sector, which is spread across organisations such as universities, government departments and agencies, PSREs such as the Met Office, the Natural Environment Research Council (NERC) and its research institutes, as well as some NGOs and the private sector. NERC is the major provider of public research funding for environmental research and maintains, directly or indirectly, most of the research infrastructure. In the coming decades, UK infrastructure will support the community to foster the partnerships, resources and technology required to work in increasingly innovative and collaborative ways.

6.1 Overview of current capability

Today's infrastructures supporting UK environmental research and innovation include ships, aircraft, satellites, high-performance computers, advanced modelling and simulation, data and sample archives, exploration and analysis software and lab-based facilities, as well as in situ measurement networks, farm- and landscape-scale experiments and collections such as geological cores/geoscience data sets and biological collections. Environmental infrastructures have a global footprint, cutting across the whole Earth system, and are designed, supported and delivered in partnership with multiple international research funders and users.

The Landscape Analysis[18] showed 16% of UK infrastructure cover an element of environmental research. The overwhelming majority of infrastructures within the environment sector (96%) collaborate with other infrastructures and organisations and 86% collaborate internationally. The analysis showed 71% work directly with UK businesses and 58% work with the public policy sector. 70% of UK environment infrastructures have an expected lifespan of more than twenty-five years. Others, such as supercomputing hardware, require a regular cycle of upgrades to maintain a world-class capability.

The UK has particular strengths in:

- Remote research stations, such as the Antarctic stations, which require maintaining infrastructure in geographically remote and harsh environments
- Large research observational platforms such as the UK's research ships, including the RRS Sir David Attenborough due to come into operation in 2020 and the Facility for Airborne Atmospheric Measurements (FAAM) research aircraft
- Large-scale national and international observing networks that enable us to monitor change across a range of areas from atmospheric to hydrological and ecological and timescales, alongside curation of long-term monitoring records

- Simulation and prediction of weather, climate and air quality on timescales from hours to centuries
- Partnerships facilitating contributions and access to international facilities, such as Earth-observing systems with European agencies and major international field experiments
- Autonomous measurements in remote and inaccessible environments, including novel sensor development and Earth observation for remote sensing and innovative field measurements
- Environmental data services, underpinned by 'big data' analytical technologies such as the Joint Analysis System Meeting Infrastructure Needs (JASMIN) computing platform
- Analytical observation services including carbon-dating and isotope facilities
- Collecting, storing and making available environmental specimen stores such as ice cores, geological cores, DNA and collections of soil, plants and algae

6.2 Future direction

The scale of the challenges and opportunities for the environment sector are immense. The global pace of demographic change is driving increasingly severe and frequent environmental impacts from growing demands and pressures on environmental resources. The study of environmental science, including the use of infrastructure, is critical to ensure water, food and energy security by managing the Earth's resources, resilience to natural hazards, mitigation and adaptation to climate change, and more. These challenges are coupled with opportunities, due to the increasing availability and quality of environmental data, advancement of digital capabilities, fast-paced development in sensing, automation and AI and improved forecasting skill from hours to decades.

The sector is evolving beyond identifying challenges to proposing and implementing solutions, recognising the imperative to improve our understanding of the environment and how it is changing in order to propose the correct interventions. Delivering on this ambition relies on continued access to high-quality infrastructure to reach, observe, model, simulate and predict our complex environment as well as how humans impact on and are affected by it. It means harnessing the major technological opportunities of the future to transform our existing capacity, supporting the development of next-generation sensing and Earth observation capability, facilitating whole-systems approaches and capitalising on supercomputing capability to glean new insights and understanding from unprecedented volumes of environmental data.

This environmental infrastructure will aim to increase capability while driving down energy costs, in line with Industrial Strategy ambitions for Clean Growth and commitments to reduce UK emissions.

Environmental science is a global endeavour and its infrastructure has a global footprint, essential for ensuring worldwide environmental observation, monitoring and prediction. This is an opportunity for the UK to lead the world in supporting infrastructure for science-infrastructure that is broad in scope, spans multiple areas of scientific enquiry across borders and is highly collaborative, including in ensuring that diverse publics are able to engage to enhance data collection and research itself.

The UK is already at the forefront of applying the latest technologies to Earth and environmental observation, simulation and prediction. The sector is well placed to use infrastructure investment to maintain a global lead. Stakeholder feedback on the Progress Report has moved forward the themes and approach, including an increased emphasis on the opportunities presented by the potential applications of 'big data', new technologies around sensing for observation that are enhanced by mass participation in the research process, computing and AI.

Low-carbon exploration and beyond: Exploring our globe's farthest reaches is vital to understanding environmental change. next-generation large infrastructures, such as research ships, have to respond to the challenge of increasing capability while driving down energy use and costs, supporting a reduction in emissions in line with UK ambitions for clean growth. For example, fleets of autonomous vehicles can provide opportunities to survey greater volumes over space and time, particularly in extreme, remote and expansive geographies, such as the polar regions and oceans, without the high carbon and other environmentally detrimental footprints of existing research ships, stations and other infrastructure.

Sensor and data-collecting networks: Technological advances in low-cost communications – such as mobile phone networks, batteries, miniaturisation and embedded computing and data processing – offer significant potential for increased environmental monitoring. The challenge of developing sensors and instruments able to capitalise on this is significant, including how to exploit mass-market sensors and sensors that are used for an alternative primary purpose for environmental information, to make the most of opportunities presented by a highly connected, data-rich world. Environmental observation, such as Earth observation from satellites, is vital to deliver new insights into all areas of the environment and equipping us with the ability to detect change and provide information over unprecedented spatial and temporal scales, including our growing ability to 'nowcast' the environment.

The exascale challenge: At all scales, from the global to the local, we rely on innovation in environmental modelling, simulation and prediction to ensure that society is forewarned and can take action. The increasingly skilful simulation of complex environmental systems is providing a computational laboratory for scientists seeking to understand how the complex Earth system works and how it is changing. However, the supercomputing power needed to further these complex simulations and predictions is highly energy-intensive. Developments in hardware design are aiming to make continued growth achievable and sustainable. Known as the exascale challenge, this will require major changes to the codes underpinning the current models used to simulate and predict, an integral part of the UK environmental science infrastructure, which can take years to develop and test. E-infrastructure challenges and requirements are discussed further in Chapter 8.

The data revolution: There has been a step-change in the availability of data on the environment, bringing together information gathered, for example, from remote sensing, ground-based sensor networks or genetic data, alongside citizen science data and data mined from online sources, including social media. Data science and AI methods are required to make sense of these high volumes of complex information, which varies significantly in quality. By 2030, systems will need to seamlessly connect different types of observations, from ground sensors to satellites, with integrated models and simulations that can be rapidly accessed by multiple users.

Building on existing strengths: Responding to future challenges and opportunities includes the need to maintain and evolve the UK's existing high-performing infrastructure – from the RRS *Sir David Attenborough* to the many services and facilities that form the backbone of UK environmental science – to ensure we build on our existing strengths and continue to deliver world-leading capability.

Building global communities: Addressing many of the environmental challenges of the present and future requires an increased emphasis on larger, multidisciplinary infrastructures. This will involve co-locating environmental scientists with researchers from beyond the traditional community, such as engineers, mathematicians and social scientists, alongside maintaining strong relationships with existing key partners in the UK and internationally, such as the UKSA and ESA on satellite observation.

Translating environmental knowledge into actionable advice requires understanding the needs of and fostering connections to the wider worlds of business, policy and society. Environmental science infrastructure needs to be integrated with and facilitate interactions across domains and sectors, including strengthened cooperation between scientists, industry, service providers and local communities.

6.3 Future requirements and opportunities

We have developed four themes to use as a framework to guide priorities for national research and innovation infrastructure to 2030, encapsulating the processes, activities and needs of world-leading infrastructure in the UK (Figure 15). These themes and framework draw on significant stakeholder consultation, feedback on the Progress Report, and the drivers and opportunities for the environment sector. The ambitions of each theme can be enabled through actual, digital and distributed laboratories, capitalising on developing technologies and data availability. Within the strategic framework, these themes are interconnected, offering a model of integrated infrastructures where the outcomes and knowledge derived from research feed back into the scientific questions that inform how we continue to explore our environment in the future.

Within each of the following themes we present some potential opportunities for future infrastructure capability. As described in Chapter 2 these are at different stages of development. Some opportunities need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered, whilst others are more developed and could be implemented sooner.

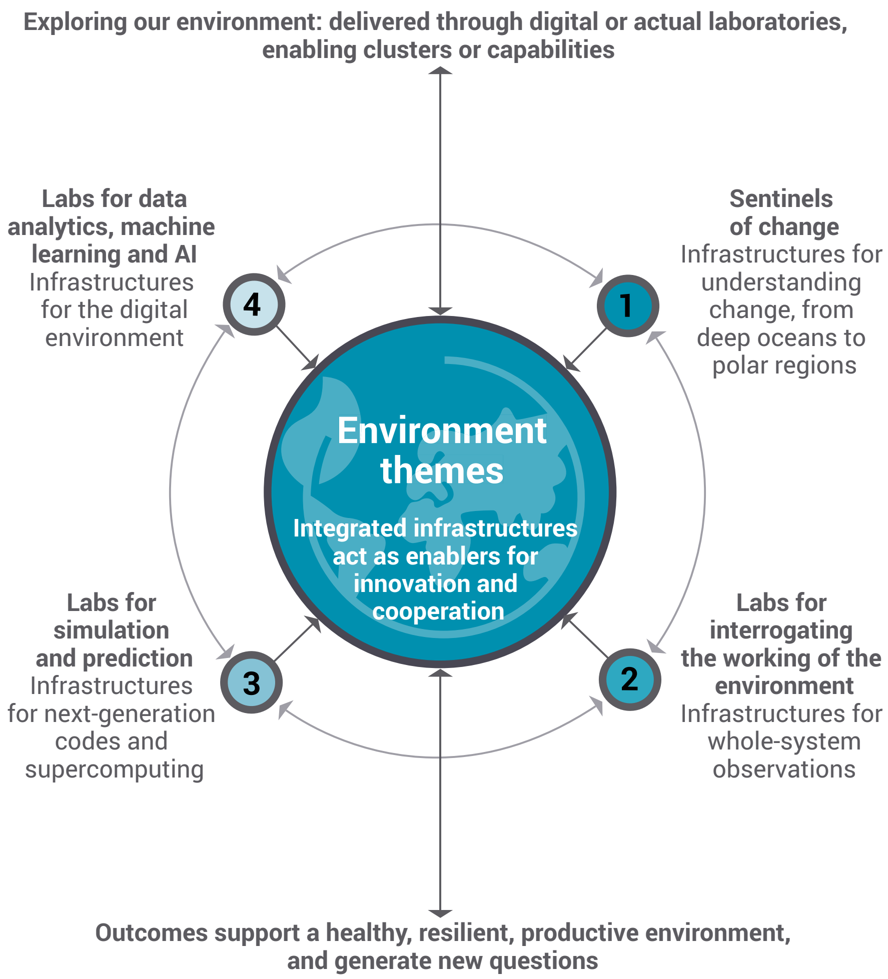


Figure 15. Environment sector infrastructure framework.

Theme 1: Sentinels of change

We live in a time of unprecedented human-driven environmental change. Rising global temperatures are having widespread and dramatic impacts on the natural world, especially in some of its most remote and harsh environments. These far reaches of the globe act as sentinels of change, where the markers of global warming are seen most clearly, such as the dramatic loss of Arctic summer sea ice and major biodiversity losses. Research and innovation infrastructure will allow us to understand some of the most hard-to-reach and extreme environments on Earth, from the polar regions to the oceans, to understand how rapidly they are changing and to provide us with early-warning systems of dangerous climate change. Responding to the challenge of increasing capability while driving down energy use and costs, the UK will support major infrastructure including the use of autonomous vehicles, to monitor and observe these sentinels of change across greater volumes of space and time.

Theme 1: Sentinels of Change	
How this area can be progressed/indicative approaches	
Robotics and autonomous systems for the environment	Investment in autonomous and remotely piloted vehicles for air, land and ocean, miniaturised sensors for use as robot payloads or in sensor networks, and the machine learning and AI architectures to exploit fully the data generated. A key element would be to support partnerships with industry to develop multi-mode vehicles, swarm deployment and high-altitude pseudo-satellites.
Next-generation global ocean observations using transformative technologies	Investment here could transform the way we see and understand our oceans, by allowing the UK to adopt and deploy a systematic, coordinated and adaptable multi-platform observing array as a key component of its national infrastructure. An internationally networked group of continuous, basin-scale platforms and sensing technologies would ensure the UK leads understanding of ocean systems and the technologies to deliver this, matching our scientific leadership with technological prowess. This would also capitalise on UK leadership in marine technology development and address major gaps in our understanding of how oceans are evolving under the pressure of human impact.
Next-generation global ocean observations platform: semi-autonomous ships	Assess the potential for a fifth-generation, semi-autonomous research ship beginning with the development of autonomous vessels. With the potential for exploring large parts of the ocean, it could act as a command platform for multiple swarms of unmanned underwater vehicles (UUVs). The infrastructure could deliver globally extensive measurements, which are key to unravelling the causes of change in the oceans and attributing human-induced change relative to natural long-term variability.

Other areas to explore:

Alongside these indicative approaches, infrastructure will drive forward technological capability and expand the scale of our global monitoring. New technologies and infrastructures will also allow us to reduce carbon and other detrimental environmental footprints. This could be achieved through:

- Facilities for field-testing instruments and components, allowing the UK to become world-leaders in instruments specified to -50°C
- The development of platforms capable of running for long periods with minimal interference in remote areas to support a variety of geophysical, atmospheric, space weather and biological science
- Infrastructure to monitor the sea floor and sub-sea floor, such as a test bed site to ensure that the environmental impact of exploiting the seabed is understood and the risks are mitigated
- Technologies (including molecular technologies) to understand changes in species composition and community structure to help understand how environmental changes are impacting on critical species, for example using e-DNA
- Zero carbon for polar or remote research infrastructure

CASE STUDY:
Autonomous fleets: exploring our oceans

Over the past fifteen years, UK infrastructure investment has created the largest and most diverse fleet of robotic research vehicles in Europe, including ten thousand items with a collective value estimated at £20 million. These unmanned, untethered robotic vehicles have vastly increased the reach of scientific research in our oceans and spell the future for low-carbon ocean exploration.

Operated from the UK's research ships and developed at the National Oceanography Centre (NOC) and the Scottish Association for Marine Science (SAMS), these vehicles go further and deeper than any commercial or military capability. They can remain at sea for many months, operating in the most extreme and remote oceanic environments on Earth, from collecting data from beneath Antarctic ice sheets to 6,000m below the surface. Two UK companies now manufacture, sell and export marine robotic vehicles underpinned by this technology, attracting inward investment and international clients.

NOC

Theme 2: Labs for interrogating the working of the environment

Effectively managing our natural resources relies on understanding the impact of climate change on the health of our soil, ecosystems, coastal and marine environment and more. People's health relies on understanding the quality of the air we breathe, the water we drink as well as our food security. We need to understand the health and resource potential of our oceans, including the extent and impact of the widespread issue of plastics, to support interdisciplinary solutions and understand their impact. Infrastructures within the environment sector can address global challenges, for example tackling AMR by supporting molecular advances and bio-environment approaches, in tandem with the ambitions outlined in Chapter 3.

Models used to simulate, predict and interrogate the workings of the environment need information from networks of sensors and instruments. These need to detect change with increasing detail and accuracy, from air quality monitoring to weather and climate observations. There are opportunities to invest in major infrastructure to observe whole systems over time and space, and which harnesses new technologies and developments such as miniaturisation, new battery technology and mobile phone networks. There is a real opportunity for the development of low-cost opportunistic remote-sensing techniques and the exploitation of mass-market sensors and technologies, to utilise sensors that are deployed for an alternative primary purpose other than obtaining meteorological information. Working with partners and the public will ensure infrastructures can enhance data collection, especially from local communities where any infrastructure is based.

Theme 2: Labs for interrogating the working of the environment	
How this area can be progressed/indicative approaches	
Airborne atmospheric measurements for climate, weather and hazard research	Investment in research aircraft (FAAM) would support requirements for measurements of atmospheric pollution, radiation, clouds, aerosols and winds at unprecedented resolutions. This would match the needs of state-of-the-art prediction systems and improve our capability for detection, quantification and attribution of air pollution. Such infrastructure would exploit emerging technologies including remote-sensing techniques, e.g. Light Detection and Ranging (LIDAR), radar and in situ state-of-the-art sensors, to enable cutting-edge airborne atmospheric measurement and monitoring. This would underpin high-resolution weather and climate models and allow more realistic modelling. It would also enhance the UK's capability to respond to atmosphere-based emergencies such as volcanic ash, pollution incidents, fires and weather hazards.
Energy and magma test bed	Creation of a first-of-a-kind magma monitoring observatory in Iceland would deliver a step-change in the ability to monitor magma, potentially unlocking a new source of geothermal heat, and boost resilience and responses to volcanic eruptions in populated areas. It could also support innovation for new drilling technologies, sensors and robotics.
Geoenergy observatories: geothermal and heat storage research and demonstrator facilities	Consider options for geological test beds to support research into a range of geothermal and heat storage technologies. This could test regional viability of low-enthalpy geothermal and heat storage technology and de-risk the supply chain. Several options exist for establishing demonstrator facilities: for example, developing the existing UK Geoenergy Observatories (UKGEOS) site in Glasgow or nearby with additional boreholes, and new geothermal research field sites and hot sedimentary aquifer facilities.
Geoenergy observatories: CO_2 storage test bed	Consider options for a CO_2 storage test bed site to investigate offshore geological storage of CO_2 as a potential technology to support the transition to a low-carbon economy. It could help de-risk costs, ensure risks to the environment are understood and mitigated, and build confidence and capability in CO_2 storage.
Landscape laboratories	Enhanced integrated networks of sensors could be designed to measure a range of interconnected physical, chemical and biological processes that define our environment and that we depend on for our water and food supplies and protection from natural hazards. A priority would be to create a laboratory for flood and drought resilience, which could utilise the latest technologies and innovative approaches to collect measurements at appropriate spatial and temporal scales. This would enable better understanding of flood and drought risk and hence better predictions and increased resilience.
Intelligent marine observing system	Consider options for a UK coastal and shelf-sea observing network and centre of excellence, including building new state-of-the-art sensors and autonomous technology with enhanced connectivity and increased intelligence (AI). This network of next-generation marine sensors, deployed through a range of marine autonomous and platform-based observing systems, would provide real-time data generation, processing and analysis.

How this area can be progressed/indicative approaches *cont.*

National infrastructure for climate and weather observations	Invest in observational infrastructure to provide high-resolution meteorological and climate measurements to develop, validate and initialise a new generation of atmospheric models. This would transform the UK's ability to address two of the hardest problems in meteorology: prediction of deep convection and the impact of boundary-layer dynamics on local-scale hazards and on the larger-scale atmosphere. It would enable improved forecasting on a range of timescales of high-impact weather extremes, such as heavy rainfall, high winds, hail, lightning and fog. It could also act as a test bed for new technological developments in novel instrumentation.
Research infrastructure to monitor air pollution	Invest in the creation of integrated, open access experimental air pollution infrastructures that enable the long-term study of atmospheric change across environments (e.g. indoor, urban, rural). This would enable detection, quantification and attribution of air pollution and provide science that can deliver technical, behavioural and policy solutions to reduce overall public exposure, both in the UK and internationally. This could support new equipment, new field facilities to study indoor versus outdoor exposure, technology development and enhancement of laboratory capabilities.
Research infrastructure for tackling environmental hazards and risks	Next generation environmental science infrastructure needs to be able to use next generation technologies. This could be through major upgrades to existing infrastructure or fundamentally new designs which are flexible, incorporate digital technologies and lead to a step-change in the scale and speed of our ability to predict, respond and mitigate environmental hazards. Detailed options would need to be scoped, including matching leading business and scientific capability to inform future innovation.

Other areas to explore:

Alongside these indicative approaches, the UK could consider developing its capability in the following types of area:

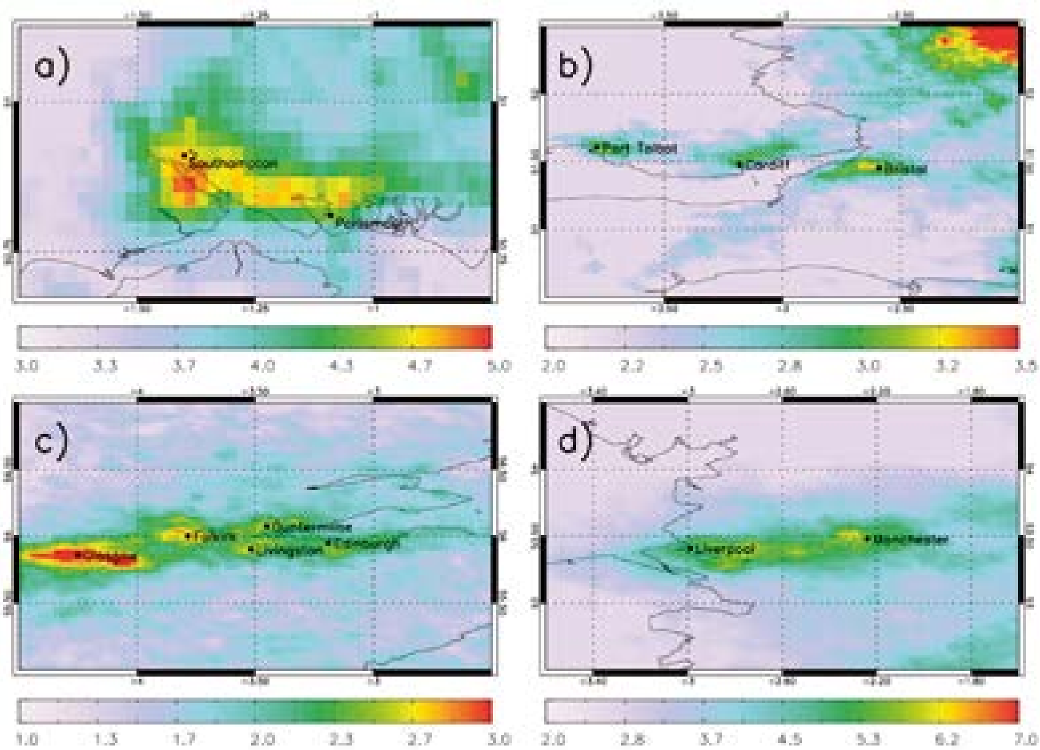
- A global facility network enabling and enhancing greenhouse gas observations, deploying existing instruments to multiple worldwide locations and developing new improved instrumentation, to support modelling of greenhouse gas budgets and enhanced understanding of global sources and sinks, and inform international action to tackle climate change
- A national community network of soil behaviour experiments, exploiting new innovation and technologies that generate data to capture the impacts of multiple stressors on soil function across national landscapes, to inform future land-management mitigation and adaptation planning
- Linked networks of observatories and mobile monitoring systems allowing analysis, detection of trends and forecasting of natural hazards
- Facilities for measuring fracture and failure to enhance understanding of environmental and material science, contributing to fundamental knowledge of geophysical processes
- Infrastructure to enable improved national resource and hazard analysis and management through enhanced geophysical survey and monitoring capacity
- Remote sensing systems for urban environmental science
- Remote sensing and observation of whole-system changes such as in marine environments, for example monitoring the impact of interventions to tackle the plastic pollution issue

- Natural laboratories allowing research to take place at the landscape scale over decades
- Integrated networks of sensors that combine measuring physical and chemical processes with measuring biological changes and understand impacts on biodiversity within a particular habitat or at a landscape scale

CASE STUDY:
Earth Observation: our environment from space

Satellite technology is increasingly integral to environmental observation and modelling. From long-term CryoSat-2 data helping scientists track rapid changes in the Arctic to researchers at the Centre for Ecology & Hydrology building detailed land cover maps of the UK, Earth observation is essential to build a clearer picture of our Earth systems and changing environment:

- Data from satellite-based remote sensing, including exploiting ESA-EU satellite data, informs cutting-edge environmental modelling and simulation through the JASMIN supercomputing platform
- British Antarctic Survey researchers have worked with commercial satellite companies to provide high-resolution images to track whales, penguins and albatross from space, informing global conservation efforts
- The ESA BIOMASS satellite will use new technology developed at the National Centre for Earth Observation to create 3D maps of the world's forests, measuring the weight of the wood held within them and the height of the trees, boosting understanding of the global carbon budget
- Satellite images from the Tropospheric Monitoring Instrument (TROPOMI) on the Sentinel 5-P satellite allow for high-resolution assessments of UK air quality from space. Alongside surface measuring this provides critical information on UK pollution sources or hotspots, hazardous pollution episodes and changes over time



Richard Pope NCEO/University of Leeds

TROPOMI TCNO2 (×1015 molecules cm−2) for JJA in 2018 for the following UK regions: (a) Hampshire, (b) West Country/South Wales, (c) Central Scotland and (d) Greater Manchester/Merseyside. Note the difference in spatial scale between panel (a) and panels (b)–(d).

Theme 3: Labs for simulation and prediction

Environmental science is increasingly reliant on manipulating data, with industry and policy users being increasingly dependent on detailed information products. Information and insights gleaned from observing our environment inform sophisticated models that can simulate and predict environmental hazards and change, supporting efforts to respond to and mitigate. This is seen in major advances in weather and climate forecasting ability. The increasing skill of these models, combined with big investments in supercomputing, give the UK access to world-class computational laboratories to probe the workings of complex systems and explore potential responses to environmental change. Alongside investment in underpinning e-infrastructure (Chapter 8), investment in infrastructure to simulate and predict environmental systems will be needed to ensure the most robust and accurate modelling of likely future scenarios. Deriving the best possible intelligence from models for simulation and prediction requires increasing capabilities in supercomputing, coupled with the development of next-generation codes and new analytical techniques such as machine learning and AI.

Theme 3: Labs for simulation and prediction	
How this area can be progressed/indicative approaches	
World-class capability in supercomputing for Earth system simulation and prediction, including Met Office computing facility and NERC/Met Office partition (MONSooN)	Enhancing UK Earth system simulation would enable deeper understanding of the complex processes and interactions that determine Earth system behaviour and responses (e.g. to increasing greenhouse gases). This infrastructure would deliver advanced prediction systems across all timescales from hours to centuries, and from the local to the global, to enable preparedness, adaptation and mitigation of environmental risks. Exploiting simulation ('digital twinning') to provide large synthetic event sets for a changing environment would enable better estimates of risk – especially risk associated with extreme events. Use of very-high-resolution simulations ('computational laboratories') to advance understanding of processes and provide learning data for AI and machine learning algorithms would improve parametrisation for global Earth system simulation.
Next-generation codes for exascale computing platforms	Re-writing of major simulation codes (e.g. the Met Office Unified Model) to exploit next-generation computing technologies would deliver cutting-edge UK infrastructure capability for simulating and predicting our environment, e.g. climate and weather.

Other areas to explore:

Alongside these indicative approaches, the UK could consider developing its capability in the following types of area:

- Integrated systems, exploiting state-of-the-art numerical simulations and integrated monitoring, to attribute specific environmental and Earth system changes to specific human or natural drivers

CASE STUDY:
Enabling resilience through hazard prediction

UK supercomputing infrastructure delivers improved accuracy in predicting hazardous weather such as flooding and snow storms, protecting lives and saving millions by enabling damage limitation. A partnership between NERC and the Met Office, the MONSooN supercomputing capability and its successor MONSooN 2 facilitate collaboration in climate and weather modelling. The partnership provides a common computing platform, post-processing capability, a fast data link and access to data archives:

- Improved weather forecasting has saved £76–127 million per year in reduction in flood damage
- Reduction in the £500 million per day cost to the economy of heavy snow, and reduction in cold weather-related death among vulnerable people
- More accurate and earlier flood warnings during the winter storms of 2013/2014 protected a million homes, saved £2 billion in UK insurance pay-outs and avoided £2.6 billion of lost working in London
- Incorporating atmospheric measurements from the UK's cutting-edge research aircraft (FAAM) in Met Office weather models has improved accuracy and helped the Environment Agency, the NHS, local authorities, agriculture and transport meet weather-related challenges

Flooding, 27 September 2012: the River Ouse overflows following a period of heavy rain and floods the streets of central York, UK.

Theme 4: Labs for data analytics, machine learning and AI

Making effective use of unprecedented volumes of environmental data to deliver environmental insight and improved prediction will require major investment in 'big data' systems, data analytics, machine learning and AI. The information and analysis generated will aid decision making, for example around resilience to natural hazards, climate adaptation and land-use management on local and national scales. This infrastructure could include interfaces with end-users, such as businesses, where there is a need for accessible data to help understand and mitigate against the risks to supply chains and business models from environmental change and hazards.

Theme 4: Labs for data analytics, machine learning and AI	
How this area can be progressed/indicative approaches	
Operational-standard Earth observation data-processing centre	An Earth observation data-processing centre would maximise the use of Earth observation data and its potential to be brought together with other data sets. This should build on investment such as the JASMIN supercomputing platform and harness partners' resources in a combined operation to enable lead organisations to better predict long-term environmental change and natural disaster risk.
Network of real-time distributed units for biological, chemical and physical data	Consider the creation of the UK's first national network of real-time distributed novel monitoring sensors and related AI tools for biological, chemical and physical data. This would provide a step-change in our ability to study environmental processes in realtime, over long periods, in a holistic way, supporting fundamental and applied research across a range of disciplines. Data would be used to aid decision-making around climate adaptation and land-use management, providing a means to prevent or reduce the impact of hazards.

Other areas to explore:

Alongside these indicative approaches, the UK could consider developing its capability in the following types of area:

- Exploring options for interfaces through which businesses would be able to understand the risk to their business model and supply chains from climate change and other environmental drivers
- Interconnected networks with digital systems data analysis, where decisions and actions could become automated giving users access to data to solve different, larger and more multidisciplinary problems

CASE STUDY:
Digitising UK science collections

The UK is home to vast collections of scientific specimens, from the Natural History Museum's (NHM's) diverse collection of 80 million specimens to the 8.5 million plant and fungi samples from across the globe at the Royal Botanic Gardens, Kew. UK-wide collections provide a historical evidence base used to address current societal issues ranging from climate change and biodiversity loss to food security and human health, and ongoing digitisation will increase researchers' access to UK collections and boost their impact. Currently, 20% of the Kew collections is digitised and available online. Around 4.3 million of the NHM's 80 million specimens are digitized and 16.8 billion collection records have been downloaded from their data portal.

Digital collections enable new 'big data' research. For example, new models of the potential spread of Zika virus were created using digital records of historical mosquito collections. Mapping data about the distribution of relevant mosquitoes against population data has helped identify areas at risk of Zika exposure. Insights like these inform and improve decision-making and could help to limit the spread of the virus and target those most at risk.

The UK is now collaborating with European partners to unify natural science collections into one digital repository and open up the potential of huge data sets over time and space to researchers worldwide. The Royal Botanic Garden, Edinburgh, and the NHM are leading the UK's involvement in DiSSCo, a multi-partner international initiative that brings together the collections of 115 institutions across twenty-one countries, representing 1.5 billion specimens and more than 5,000 scientists.

Royal Botanic Gardens, Kew

Digitisation of botanical specimen samples from the science collection at Kew.

Chapter 7: Energy sector

andreas160578 from Pixabay

Energy is a multidisciplinary sector spanning the technologies required to generate transport and store energy, the use of energy by industry and the general public and aspects of how energy impacts on the environment. Energy research and innovation, also draws on an understanding of complex systems, robotics, remote monitoring, control and digital technologies and the social sciences to explore the policy, business model and consumer behaviour implications of the energy system. Energy R&D priorities are driven by the need to achieve the UK's 2050 net zero target and clean growth by providing low- carbon, affordable and secure energy for the UK.

Growing UK income while cutting greenhouse gas emissions, alongside the provision of support for affordable energy, is at the heart of the Clean Growth Strategy[45], which sets out the actions needed to cut emissions, increase efficiency and help lower the cost of energy to consumers and businesses. As part of these goals, the UK Industrial Strategy seeks to support "automotive, aerospace and construction industries to increase their share of global markets as they shift to clean energy sources and efficient new materials…to lead the development of new markets in areas such as smart energy systems and… the use of renewable biological resources from land and sea to produce food, materials and energy". In support of this, the government has announced Sector Deals for the offshore wind[76] and the nuclear[77] sectors, the Industrial Strategy Clean Growth Grand Challenge, as well as being the first major economy in the world to pass a net zero emissions law.

The UK is well placed to take advantage of the economic opportunities with a broad range of low-carbon industries, a strong research base and support for innovation and excellence in the design and manufacturing of leading-edge technology. It is estimated the UK low-carbon economy could grow by 11% per year between 2015 and 2030[78].

The major public sector funders for energy research and innovation in the UK are BEIS and UK Research and Innovation. Several UK Research and Innovation councils support research and innovation programmes in energy, predominantly EPSRC but also ESRC, BBSRC, NERC, STFC and Innovate UK, reflecting the cross-cutting nature of the challenge[79].

7.1 Overview of current capability

Much of the underpinning research and innovation that supports work in the energy sector is provided by infrastructures across the landscape, particularly those from the environment, physical sciences and engineering and e-infrastructure sectors. The Landscape Analysis reflects this with 53% of physical sciences and engineering infrastructures, 44% of environment sector infrastructures and 46% of e-infrastructures and data infrastructures indicating strong links to the energy sector.

In the last fifteen years, there has been a growth in investment in energy R&D and associated infrastructure, as clean energy has become a priority and the industry has expanded. In our Landscape Analysis, 82% of energy-focused infrastructures are less than fifteen years old.

The current infrastructure is balanced between an academic and industrial focus with 50% declaring a balanced user base, 27% being more discovery-focused and 23% being commercially driven. The applied nature of energy infrastructure is exemplified in the offshore renewable industry, which increased its installed capacity to over 8GW in 2018 from almost nothing in 2008. This rapid increase was made possible by investment in facilities such as the Energy Technologies Institute and the Offshore Renewable Energy Catapult. These facilities have helped develop and prove the technologies and accelerate installation.

The UK has been building infrastructure capability in many key areas such as offshore renewables, batteries and nuclear. We are starting to build capability in areas such as hydrogen; however, there remain some critical capability gaps such as alternative fuels and solar power. Much of the capability lies in universities, dedicated institutions such as UKAEA and the National Nuclear Laboratory (NNL) or technology developers such as the Catapults. There is also significant analytical capability in multidisciplinary infrastructure such as Diamond. Most energy R&D-focused infrastructures are largely publicly funded and the majority of development- and deployment-focused infrastructures are industry-funded. Where there are more nascent markets, such as carbon capture and storage (CCS), there are parts of the sector that require government support for higher TRL activity to prove and de-risk the technology. The majority of these energy infrastructures (73%) have a strong e-infrastructure requirement and 63% see e-infrastructure needs becoming more important in future years.

The UK has particular strengths in:

- **Fusion:** the UK is host to the Joint European Torus (JET), the UK Mega Amp Spherical Tokamak (MAST) and associated R&D capability at the fusion Materials Research Facility and Remote Access in Challenging Environments facility
- **Fission:** through the NNL, Dalton Cumbrian Facility and National Nuclear User facilities.
- **Energy systems:** for example, through the Energy Systems Catapult
- **Offshore renewable energy:** through the Offshore Renewable Energy Catapult, the Coastal, Ocean and Sediment Transport laboratory, the FloWave Ocean Energy Research Facility and the European Marine Energy Centre (EMEC)

The UK is also building capability in energy storage (e.g. the Faraday Institution) and energy materials research (e.g. the Sir Henry Royce Institute).

7.2 Future direction

The key drivers for the UK energy sector will continue to be affordability, security of supply and reduced carbon emissions. Energy will continue to be a key government priority as part of the Industrial Strategy and in its capacity of monitoring and regulating the sector. The ability of the sector to respond to government priorities will therefore remain paramount, but without supportive research and innovation infrastructure a timely response may not always be possible.

The highly regulated nature of this sector is critically important to future infrastructure needs. Almost no energy generation technologies can be commissioned without either certification of the technology (e.g. nuclear) or permissions for installation (e.g. offshore renewables). This means new energy technologies and their impact on the overall energy system, the environment and customer base need to be thoroughly understood before the regulator can allow them to market. Alongside the development of technology options, the wider policy and social context must also be considered. This creates a need for development, testing and certification capability.

Not all innovation is about technical innovation or market innovation. Resource availability and cost is also important. For example, the search for cheap and abundant materials to replace expensive rare-earth materials can have a significant impact on the economic feasibility of renewables and energy storage. State-of-the-art materials science research and innovation infrastructure will be needed to address these challenges.

The scale and pace of the transition to a low-carbon energy system makes future research and innovation infrastructure requirements difficult to predict. New and different types of infrastructures are needed and the number of users who require access will increase. Potential future technologies also need to be properly researched, but which should be prioritised? Resource limitations will always make it challenging to fully support all options. The current model of R&D in the energy sector supports underpinning science with strong industry engagement. Where advances are made, government and industry support is focused towards developing these underpinning ideas further. The energy sector has been a significant beneficiary of recent Industrial Strategy funding where development infrastructures have been, or will be, quickly built, e.g. the Faraday Institution.

The UK's commitment to clean energy innovation is supported by its membership of the Mission Innovation[80] programme which has objectives that include doubling state-led energy R&D by the year 2020 and the building of roadmaps to assist in innovation efforts. The programme has identified eight critical areas: Smart Grids, Off-grid Access to Electricity, Carbon Capture, Sustainable Biofuels, Converting Sunlight, Clean Energy Materials, Heating and Cooling, and Renewable and Clean Hydrogen. The UK co-leads on Carbon Capture and Heating and Cooling, and is heavily involved in most of the other themes. The priority areas map well onto the research infrastructure needs identified in this report, though the UK has strategic interests that Mission Innovation does not cover, such as nuclear fission and fusion.

The UK has a breadth of infrastructure capability but consultations over the course of this programme have identified areas where additional infrastructure investment is needed to underpin and develop certain core energy technologies. In addition, although there is good collaboration between existing facilities, more could be achieved by **building better connections** between them and new collaborative projects to create distributed national capability rather than duplicating capability in new single-site centres.

Due to the level of uncertainty around the future energy landscape, it is necessary to **maintain a minimum capability in a broad suite of technology options**, whilst focusing on key areas as they become viable possibilities. If this broad capability is not maintained then the UK will not be able to respond quickly to any global breakthroughs or shifts in energy markets. A systems-level understanding, i.e. how technologies integrate across the network and interact with the market and environment, will also be needed to inform both regulatory decisions and overarching policy.

Stakeholder feedback on the Progress Report reinforces our initial findings and key messages. There is a need for further **large-scale initiatives** similar to the Faraday Institution and significant national research laboratories around the world such as the National Renewable Energy Laboratory in the USA. Many of the themes described here require large demonstrators of multi-vector energy systems, following the example of the Integrated Transport Electricity Gas Research Laboratory (InTEGReL), and include capabilities for multidisciplinary research and innovation. Creating these larger-scale activities is particularly important in the energy sector where problems are inherently multi- and interdisciplinary. The potential for a step-change in capability lies in the integration of individual research areas into the overall energy system. Large-scale initiatives: enable a critical mass of research and innovation activity; increase quality, volume and discipline reach; and can be directly informed by the needs of multiple stakeholders from business and government.

Research into **reducing the environmental impacts** of energy technologies is increasingly important. This includes the mining of materials for low-carbon energy technologies, the replacement of rare and expensive materials with cheaper and more abundant ones, improved efficiency of manufacturing processes and end-of-life management of energy technologies.

There is **potential for greater data-sharing and cyber-physical demonstrators** that could be achieved via use of Open Data platforms, cyber-physical skills and tools, along with 'big data' technologies. Such facilities could help overcome challenges associated with operation, management and product development, as well as challenges associated with resilience and reliability of the energy system.

There is a **strong reliance on e-infrastructure** in the energy sector to support research and innovation on operational challenges, system resilience, identification of vulnerabilities in the cyber and physical infrastructure of the energy system and mitigation of threats. Collecting data from end-users and energy appliances also represents a huge opportunity for the UK. Such data can enable analysis, which informs policy and product development, supports standardisation and improves system management and operation. In addition to the cross-sector computational and e-infrastructure requirements outlined in Chapter 8, this sector will need:

- Open access national databases of technical data, demographic data and behavioural data for demonstrators/laboratories to couple cyber and physical aspects of the Energy sector
- National real-time simulation capability with increased computational power, pooled resources (e.g. real-time and digital simulators) and a focus on the energy sector. This could also include national coordination of access to infrastructure and an open access data platform similar to ERIGrid (the European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out project) which connects the European Smart Grid infrastructure. This would support communication between existing and future facilities and enable enhanced testing and validation of the concepts developed in the sector.

7.3 Future requirements and opportunities

Due to the applied nature of much energy research and innovation, a significant amount of the infrastructure needs identified in this exercise and captured in the following themes are at higher TRLs.

Support for maintaining existing research and innovation capability remains a high priority and many of the options for additional capability build on or bring together existing facilities. Given the costs involved, the energy sector will evolve slowly over the next thirty years. However, the CO_2 reduction challenges that the UK faces require that low-carbon options are available sooner rather than later and the facilities and infrastructure to deliver the low-carbon options will be needed even sooner. Likewise, energy infrastructure lifecycles need to be long to ensure that regulators have test infrastructure capable of supporting their activities and that industry has a training ground for its future staff.

Within each of the following themes (Figure 16), we present potential opportunities for future infrastructure capability. As described in Chapter 2 these are at different stages of development. Some opportunities need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered, whilst others are more developed and could be implemented sooner. Where possible and cost-effective, use or participation in facilities that already exist internationally may be the most effective approach.

The most beneficial infrastructure investments will be dependent on the UK's future energy system. As this is not clearly known the opportunities described here represent the breadth of possible needs which will change if specific energy generation or transmission options are abandoned.

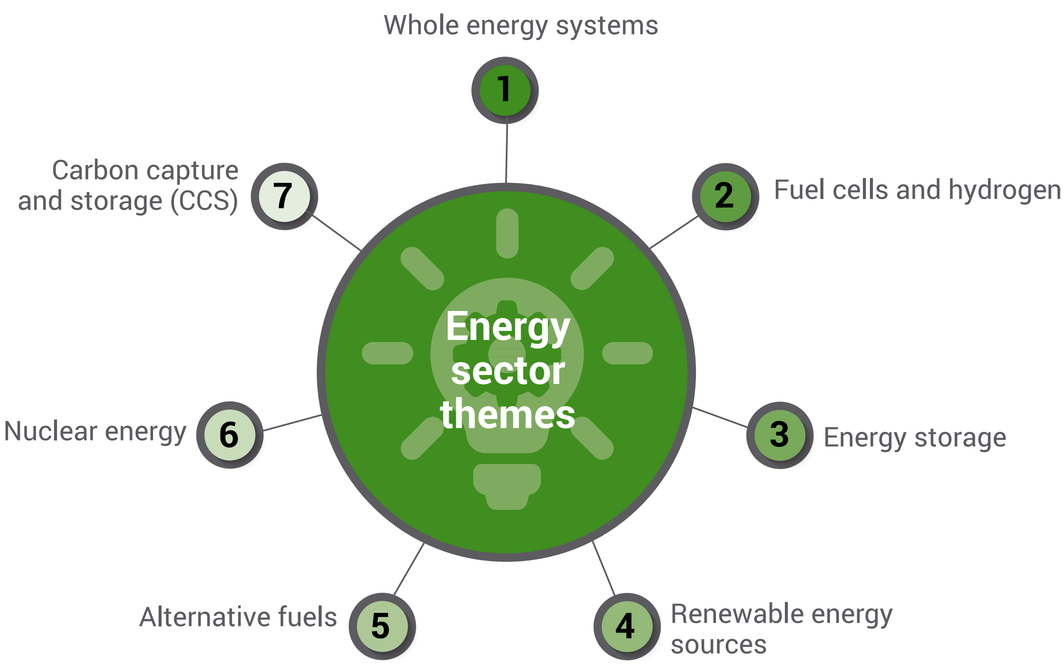


Figure 16. Energy Sector themes overview.

Theme 1: Whole energy systems (including energy demand and power distribution networks)

Whole energy systems research specifically considers multi-vector energy systems. It brings together the different elements of an energy system, such as technology options, policy and regulatory landscape, how energy is used and the energy market, to provide evidence for policymakers, regulators and energy providers. As the UK energy system transitions to become low-carbon and more decentralised, a clear understanding of how all the different elements interact is vital. Systems modelling work in universities, through several recent programmes, has begun to bring together parts of this complex system, such as at the UK Energy Research Centre, the Centre for Energy Systems Integration and InTEGRel. However, fully understanding the system requires significantly enhanced capability to digitally monitor, control and optimise the operation of each individual asset, each energy vector and the overall energy system itself, while also considering human behaviour, weather uncertainty, environmental restrictions, security and safety. The need to decarbonise heating, which generates around 40% of UK CO_2 emissions[81], is also a critical challenge for the UK. Analysis of this complex problem will also require interdisciplinary systems-level understanding.

Theme 1: Whole energy systems

How this area can be progressed/indicative approaches

Centre for energy analysis: integration of energy whole systems modelling	Invest in better integration of nationally important energy models to foster interdisciplinary research across the cyber and physical elements of a multi-vector energy system. This could be through creation of a new centre for excellence or through enhanced connectivity of existing centres.
Research facility for the decarbonisation of heat, to reduce the carbon footprint of domestic heating	Consider options for a single- or multi-site facility that would offer flexible demonstrators to develop the three main heat options (electrification, repurposing for hydrogen and district heating).

Theme 2: Fuel cells and hydrogen

Hydrogen is considered a promising pathway to enable a low-carbon economy, since it can be used in heating, transport and power applications, either by combustion or with fuel cell technologies. Hydrogen could also replace methane in gas networks although significant modification to the gas infrastructure would be required. Hydrogen storage is also possible on a seasonal scale, enabling surplus renewable energy generated in the summer to be used for generating hydrogen, which can be stored until winter when demand is much higher. Such inter-seasonal storage is more difficult and expensive to implement with batteries. If the UK considers hydrogen to be a viable option for a future energy system, then support for research and innovation infrastructure will be needed.

There are several time-limited research programmes currently active in this area: the SUPERGEN hydrogen and fuel cells consortium, Hy4Heat and HyDeploy. Our consultations identified the need for sustained facilities to support investigation of the impact of hydrogen on the current systems and develop new products and solutions. Replacing natural gas with hydrogen will affect materials, seals, lubricants and combustors. Hydrogen is also of lower energy density and therefore a greater volume will need to be pumped, possibly at higher pressure, in order to achieve the current energy levels delivered by natural gas. Lifecycle analysis research is needed to determine the most cost-effective method of generating and using hydrogen. For example, is it Steam Methane Reforming (SMR) coupled with CCS and burning in combined heat and power boilers, or is it electrolysis coupled with combined heat and power fuel cells?

Fuel cells could also be essential technologies within the hydrogen energy pathway. There remain significant challenges, including improvement to performance, reliability, robustness and reduction of cost by 2025–2030.

The indicative approaches below could be taken forward in isolation, focused on particular challenges or combined. As with many of the energy challenges, research on this theme is connected to parallel work on other key technologies. For example, SMR should not be done if CCS is not addressed and the potential for using cheap hydrogen in the gas grid also requires research on how the existing grid and appliances might be adapted to cope.

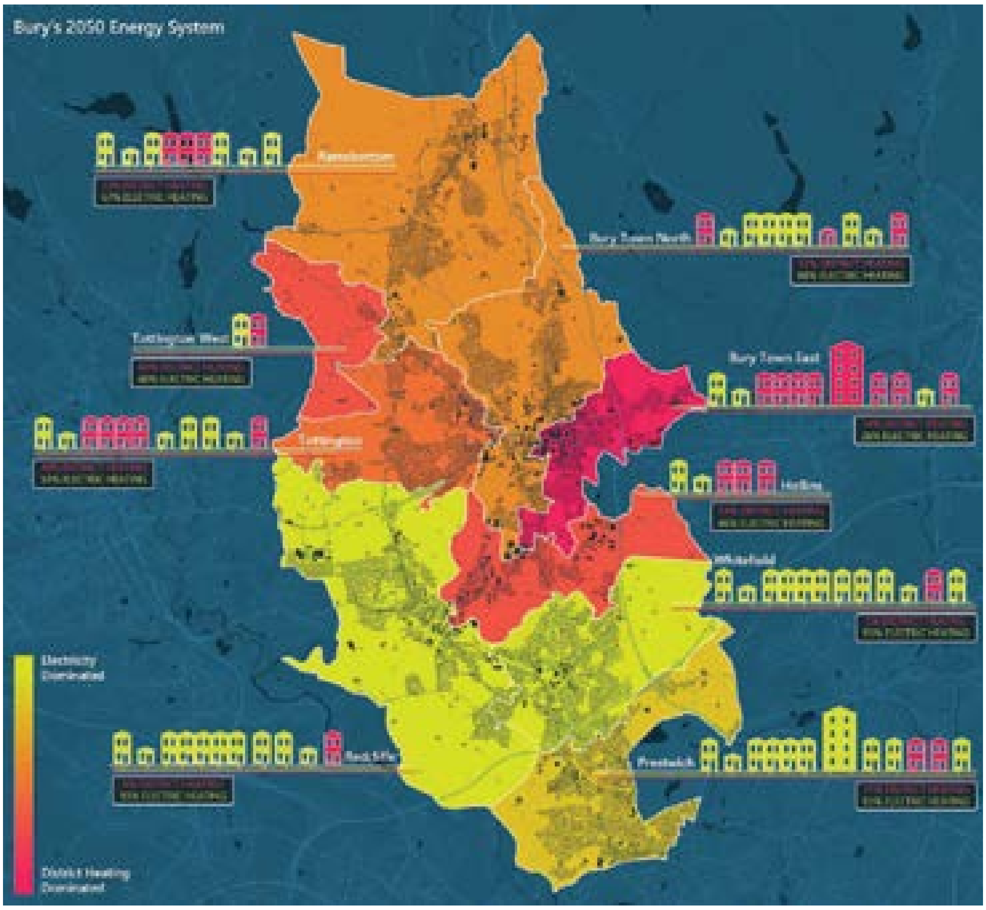
CASE STUDY:
Energy Systems Catapult facilitates local area energy planning

The importance of local area energy planning has been highlighted by the government in its Clean Growth Strategy. However, there is currently no structured planning process to establish a long-term view of how local energy systems will need to be transformed to deliver a low-carbon future. The Energy Systems Catapult (ESC) has piloted a new whole system approach with Newcastle, Bury and Bridgend: aims to achieve this by bringing together local and national government, network operators and other stakeholders to agree an efficient, least-cost solution for meeting emissions targets[82].

The project found no single approach to decarbonising the energy system could be applied nationwide, with each local area requiring a unique mix of technologies and networks. ESC's analysis also showed how the decarbonisation of heat could be achieved for less than 15% above the cost of decarbonising electricity alone by adopting a whole-system approach (i.e. considering all aspects of the system together including heat, electricity, transport, supply chains and digital, physical, market and policy structures).

Through the pilots, local authorities, energy network operators and other key local stakeholders investigated future local energy scenarios[83] to help inform innovation projects and long-term planning of energy system transformation. The ESC is now looking at how to scale-up local area energy planning across the UK.

The ESC is an independent, not-for-profit centre of excellence that collaborates with industry, academia and government to overcome the systemic barriers of the energy market. It exists to unleash the potential of new products, services and value chains required to achieve the UK's clean growth ambitions as set out in the Industrial Strategy. With more than 170 expert staff based in Birmingham and Derby, they work with innovators from companies of all sizes to develop, test and scale their ideas.



Illustrative example of a spatial energy plan developed via Local Area Energy Planning.

Theme 2: Fuel cells and hydrogen	
How this area can be progressed/indicative approaches	
Centre for the study of hydrogen use and safety of devices	Options range from a product-testing centre that enables certification of new devices, TO more substantial activity focused on developing new devices with a role in independent certification to support UK manufacturers.
A facility to develop bulk production of low-carbon, low-cost, resilient hydrogen	One or more low-carbon hydrogen production demonstrators, probably with electrolysis, would be needed to demonstrate that hydrogen can be produced and supplied to the commercial market at a competitive cost.
A research centre into the use of hydrogen in the gas grid, as an admixture or as 100% hydrogen	A centre for R&D into re-purposing the current gas infrastructure (TRL 5–8), combustion (TRL 6–8), fuel cell research (TRL 6–8) and gas storage (TRL 3–6) would facilitate research to support the transition from methane to hydrogen. This could be combined with the first or fourth fuel cell and hydrogen challenge described in this table.
A centre to research and develop the underground storage of hydrogen	To store large quantities of hydrogen inter-seasonally, a facility or laboratory could be commissioned to study hydrogen storage and distribution systems equipped with measurement instrumentation coupled with an array of boreholes. This could be part of a broader subsurface research capability that also looks at CCS and geothermal energy.
A research institute for fuel cells for the improvement of performance and reduction of cost	Consider options for an R&D facility to address the remaining challenges that prevent the wider uptake of fuel cells and research and develop fuel cells technology.
A centre to facilitate the transition from a natural gas economy to a hydrogen economy	Decision-makers need a better understanding of what a hydrogen economy could look like. A new research hub would assess the various hydrogen technology options and possible pathways that could be implemented to replace natural gas with hydrogen in the UK. This could be linked to action taken under Theme 1.

Theme 3: Energy storage

Energy storage is an important technology to support the balancing of supply and demand. It is often described as an enabling technology for renewable energy as it enables storage of surplus renewable energy at times of high generation and low demand that can then be released when demand is high. Energy storage therefore increases the flexibility of energy systems, but at increased overall cost. There are many ways to store energy:

- Electrical storage
- Thermal storage
- Chemical storage (see hydrogen and alternative fuels themes)
- Kinetic storage

Recently, there has been much emphasis on electrical storage for transport with the creation of the Faraday Institution. However, there remains a need to improve efficiencies of small-scale mobile storage thermal storage and in developing kinetic storage systems, such as compressed air, flywheels etc. Chemical storage is addressed in Theme 2: fuel cells and hydrogen.

Consultation with the community highlighted two areas of importance:

- The need to couple short-term storage such as compressed air with renewable generation to help smooth variations in generation and demand
- The need to study the interactions of users with the various energy storage options in a 'living laboratory' situation; this should encompass not only localised electricity storage but also thermal storage and could consider the technical flexibility of storage and associated costs, comparing static versus mobile energy storage applications which have different research needs

Research into advanced materials is critical for the energy sector as well as more broadly across the landscape (Chapter 1). This research is applicable to all energy themes, but has been captured here given the specific needs identified within the energy storage theme.

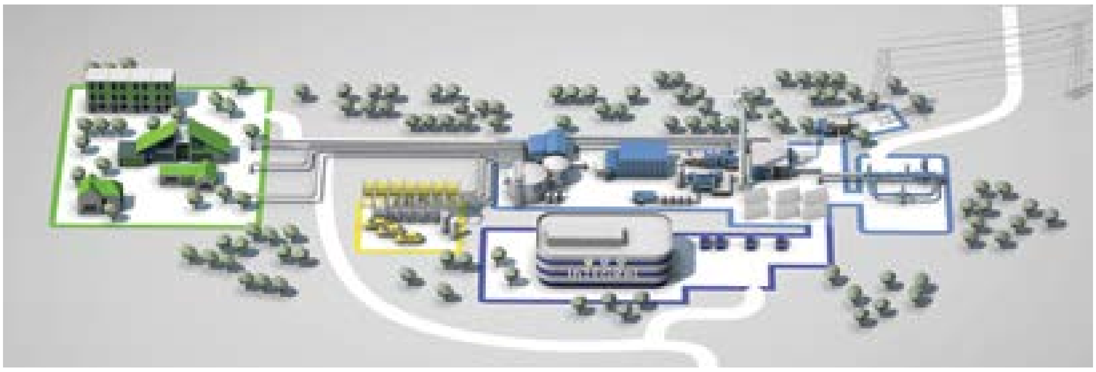
Theme 3: Energy storage	
How this area can be progressed/indicative approaches	
A 'living laboratory' for energy storage integration and local generation systems	To develop new energy systems and understand how people interact with them requires real-world studies. Creation of a 'living lab' at scale and in different environments (urban, sub-urban, mixed and industrial) would enable such studies. This could also support the study of social aspects of energy storage, such as large-scale consumer studies, to better understand how people interact with energy systems. Alternatively, this could be considered as part of Theme 1.
Large-scale offshore renewable energy storage demonstration facility	Consider options for facilities to complement the existing offshore renewable energy test facilities at the Offshore Renewable Energy Catapult. This could comprise of a wind turbine test facility where integrated energy storage technologies can be tested to demonstrate their ability to store surplus electricity thermally, kinetically, chemically or in batteries.
Emerging/new materials or technologies	New materials research is important across the research and innovation landscape (Chapter 1). An energy materials research centre could be part of a larger, cross-sector capability. The energy component would focus on synthesis, characterisation and testing of new advanced materials and could research new bulk manufacturing methods.

CASE STUDY:
Demonstrating a whole-systems approach to UK energy use

In 2017, 29% of the UK's electricity came from renewable sources, but electricity only accounts for around 20% of the UK's energy use. We must also decarbonise transport (around 40% of energy use) and heat (around 30% of energy use). A whole-systems approach to integrated electricity, gas and heat networks offers us the potential to rapidly deliver a resilient, low-carbon, least-cost energy system. However, there are many technical, commercial, regulatory and safety research questions which need to be addressed.

The Integrated Transport Electricity Gas Research Laboratory (InTEGReL) is a fully integrated whole energy systems development and demonstration facility, providing a space for industry, academia, SMEs and government to come together to explore and test new energy technologies, strategies and processes which bring transport, electricity and gas into one place[84]. Once completed, the facility will build on the unique co-location of an electricity distribution system, a gas distribution hub, a gas distribution system control room and an 'energy village' of occupied residential properties. The energy village will collaborate with and complement the work being undertaken by the £34 million ISCF/EPSRC Active Building Centre (ABC) project for which Newcastle University is a partner.

Through collaboration with industry and academia, InTEGReL plans to break down traditional barriers between gas, electricity, water and transport sectors to better utilise their assets to deliver a more secure, affordable, low-carbon energy system.



Produced by Northern Gas Networks

Theme 4: Renewable energy sources

Renewable energy sources have a vital role in securing UK's targets for reduced CO_2 emissions; two of the three possible scenarios for the UK government to meet 2050 carbon targets involve increasing the share of renewables in the energy system. This importance to the UK, coupled with worldwide growth in the use of renewables, means investing in research and innovation infrastructure has the potential to generate significant economic benefit.

There has been much investment in renewable energy centres in recent years, especially in offshore renewable energy. These investments have helped underpin the significant growth in wind power capacity in the UK over the past ten years.

Consultation with the renewable energy community identified three areas where new capability could have a significant impact:

- New solar energy devices, exploiting the UK's lead in materials technologies and specifically materials for Photovoltaics (PV), e.g. perovskites
- Environmental impact of offshore renewable energy installations, to ensure facilities are placed at the best sites for maximum efficiency and minimum impact on the marine environment
- Development of UK geothermal potential: this is an almost unexploited resource, but, little is known about its potential, long-term reliability and possible environmental impacts

Theme 4: Renewable energy sources

How this area can be progressed/indicative approaches

Solar energy scale-up facility to support the development of new Photovoltaic (PV) technologies	A demonstration facility would aid development of new PV technologies where the UK is in a leading position. This could take the form of a national centre for low-cost printed PV that supports the distributed research community in the UK by taking newly discovered structures or production techniques and developing them for full manufacturing scale and installation.
A facility for understanding large-scale tidal stream/ wind/wave energy extraction and its interaction with the environment	A large laboratory-scale wind/wave/current combined basins and measurement system would bridge the current capability gap between small-scale wave tanks and full-scale at-sea sites. Alongside this fully, instrumenting current at-sea sites would enable state-of-the-art testing and development to take place.
Geo-fluids research centre to investigate the development of UK geothermal potential	Explore options for building on the current UKGEOS facility to include geothermal heat, for example through a medium- to large-scale demonstrator capable of fundamental research on geothermal energy co-production, possibly coupled with oil and gas production. This could link to work on the underground storage of hydrogen (see Theme 2) and the subsurface laboratory for CO_2 injection and storage (see Theme 7).

CASE STUDY:
European Marine Energy Centre (EMEC)

Established in 2003, EMEC is the world's leading facility for demonstrating, testing and verifying wave and tidal energy converters (technologies that generate electricity by harnessing the power of the sea). Having hosted twenty companies from eleven different countries (including E.On, Scottish-Power and Scotrenewables Tidal Power) with thirty-two prototypes so far, more marine energy devices have been trialled at EMEC than at any other site in the world[85].

Based in Orkney, Scotland, EMEC helps developers to reduce the time, cost and risk in developing innovative renewable energy technologies through the provision of purpose-built, accredited open-sea testing facilities sited in the harshest of marine environments. EMEC offers independently verified performance assessments of the devices tested at its grid-connected test sites, as well as technical verification of devices and subsystems to satisfy reliability, survivability and performance targets.


CorPower C3 WEC deployment at EMEC Scapa Flow site.

Colin Keldie

Beyond device testing and demonstration, EMEC has worked on over one hundred R&D projects across the sector looking at marine energy sub-systems, components and infrastructure. During the last three years, EMEC has given focus to energy storage using hydrogen, pioneering the development of green hydrogen from onshore wind and tidal energy. Offering demonstration, technical and commercial support, EMEC is now also supporting the development of floating offshore wind. The development of EMEC has had a positive impact regionally and nationally, having accelerated wave and tidal energy development in the UK, as well as generating a GVA to the UK economy of £284.7 million and creating over 4000 jobs.

Theme 5: Alternative fuels

Reduction of greenhouse gas emissions in the transport sector, including road, rail, aviation and shipping, can be achieved by switching to low-carbon energy sources, including non-fossil liquid fuels. These fuels are varied in origin and include:

- Biofuels
- Hydrogen (considered in the Theme 2)
- Liquid hydrocarbon derived from CO_2
- Alternative fuels for fuel cells (ammonia, formic acid, etc.)

Biofuels are a ready substitute for liquid fossil fuels and in theory could produce quick reduction in CO_2 emissions. However, there are unanswered questions on the full carbon lifecycle analysis, the use of land for food versus fuel and what the source biomaterial should be.

Theme 5: Alternative fuels	
How this area can be progressed/indicative approaches	
Alternative fuels R&D centre	A central coordinated hub focused on identifying the options for alternative fuels would lead to a more substantial effort, similar to the Faraday Institution, and could take a broad approach to studying alternative fuel technologies and assessing their viability. This could be focused on a single alternative or could be expanded to a centre that covers all options.

Theme 6: Nuclear energy

In this section, nuclear energy includes both fission and fusion. Both technologies have common requirements and unique challenges.

Fission is recognised by the UK government as having an important role in achieving clean growth as acknowledged in the recent nuclear Sector Deal[77]. However, the sector faces several technological challenges:

- To build the capacity in design and manufacturing to deliver next-generation nuclear technologies (including Gen(III)+, Gen IV, small modular reactors (SMRs) and Advanced Modular Reactors (AMRs)
- To reduce the costs of electricity from nuclear fission
- To design and deploy nuclear energy systems that can deliver flexible heat and power
- To safely decommission the current fleet of reactors and dispose of the waste safely

Recent investments in fission infrastructure that have been made, or are being scoped, include:

- The ISCF challenge in advanced modular reactors
- Phase two of the National Nuclear User Facility (NNUF)
- A thermal hydraulics research facility

Fusion energy is also likely to play a role from 2050 onwards and research undertaken today will be critical in delivering this longer-term goal. The UK is a globally leading nation in the development of fusion, hosting the JET facility and running a parallel domestic development programme, MAST. Recent government investments in fusion facilities have begun to build the national research infrastructure:

- The Remote Applications in Challenging Environments (RACE) facility at Culham which researches robotic access to radioactive environments for maintenance and decommissioning purposes
- The Materials Research Facility develops new materials for use in fusion and fission reactors
- Hydrogen-3 Advanced Technology (H3AT), a tritium-handling facility, will provide the capability to handle demo-plant levels of fusion reactor fuels
- The Fusion Technologies Facility
- The Spherical Tokamak for Energy Production – the first phase of the work to produce a concept design for fusion energy production is under way. This project will build on the work of the MAST facility

Complementary research and innovation challenges between fission and fusion energy research are mostly in areas like robotics (removing the need for human intervention), remote monitoring and materials science. Other generic challenges include the development and manufacturing of future fuels, minimising and managing waste, plant decommissioning, regulation, public acceptability, new plant design, manufacture and operation, environmental impact and geological waste disposal. Alongside these common challenges are a range of specific questions focused on fission or fusion.

Information on future research requirements has been investigated by the Nuclear Innovation Research and Advisory Board[86]. As well as technological challenges, there are opportunities for social, economic and policy research to understand the societal challenges of nuclear energy, public understanding of issues and how the UK could deliver a transformative shift to clean growth.

Theme 6: Nuclear energy

How this area can be progressed/indicative approaches

Expanding nuclear engineering capability through a centre of excellence	Explore potential for a centre of excellence in nuclear engineering. This should complement and possibly include an expansion of the Nuclear Advanced Manufacturing Research Centre (NAMRC). Such a centre would enable multidisciplinary nuclear energy engineering to support the UK new-build programme. Additionally, demonstration sites could be commissioned in conjunction with the proposed nuclear development programmes, also supported by the work of the NAMRC and Catapults. This centre could also include wider cost reduction R&D in reactor and site construction.
Nuclear decommissioning research centre	Facilities for handling and analysing active materials would enable development and scale-up of newly developed techniques. This could include facilities to design and develop waste minimisation, treatment and management technologies in both active and non-active environments. This is a critical issue for the planning of new-build programmes in both SMRs and AMRs.
Research centre for fuel requirements for future reactors	Developing dedicated facilities to research and test the fuels of future reactors, especially accident, tolerant fuels, would help maintain and grow the UK's advanced fuel capability. This is important for both existing and future reactors, in both civil and defence applications.
Spherical tokamak for energy production (STEP)	Taking spherical tokamak studies through to the next development phase would require a large fusion demonstration reactor to develop the technology needed to generate electricity. The first phase of the STEP programme will develop the spherical tokamak approach to produce a concept design for the production of affordable fusion energy. The first year of this work is currently under way.
Thermal hydraulics research centre for reactors	A dedicated facility for thermal hydraulics research and testing would support the design and development of new reactors. Such a facility would need to cover one or more of the following areas: pressurised water, molten salts, liquid metal and advanced gas. These are areas of interest for code validation of SMRs, AMRs and any future advanced Pressurised Water Reactors (PWRs). This facility is in the initial scoping stages.
Centre or research institute for advanced reactor development	New facilities that underpin design capability to support UK ambitions for new nuclear build would enable the informed assessment and development of future reactor designs, their regulation and operation.

Theme 7: Carbon capture and storage (CCS)

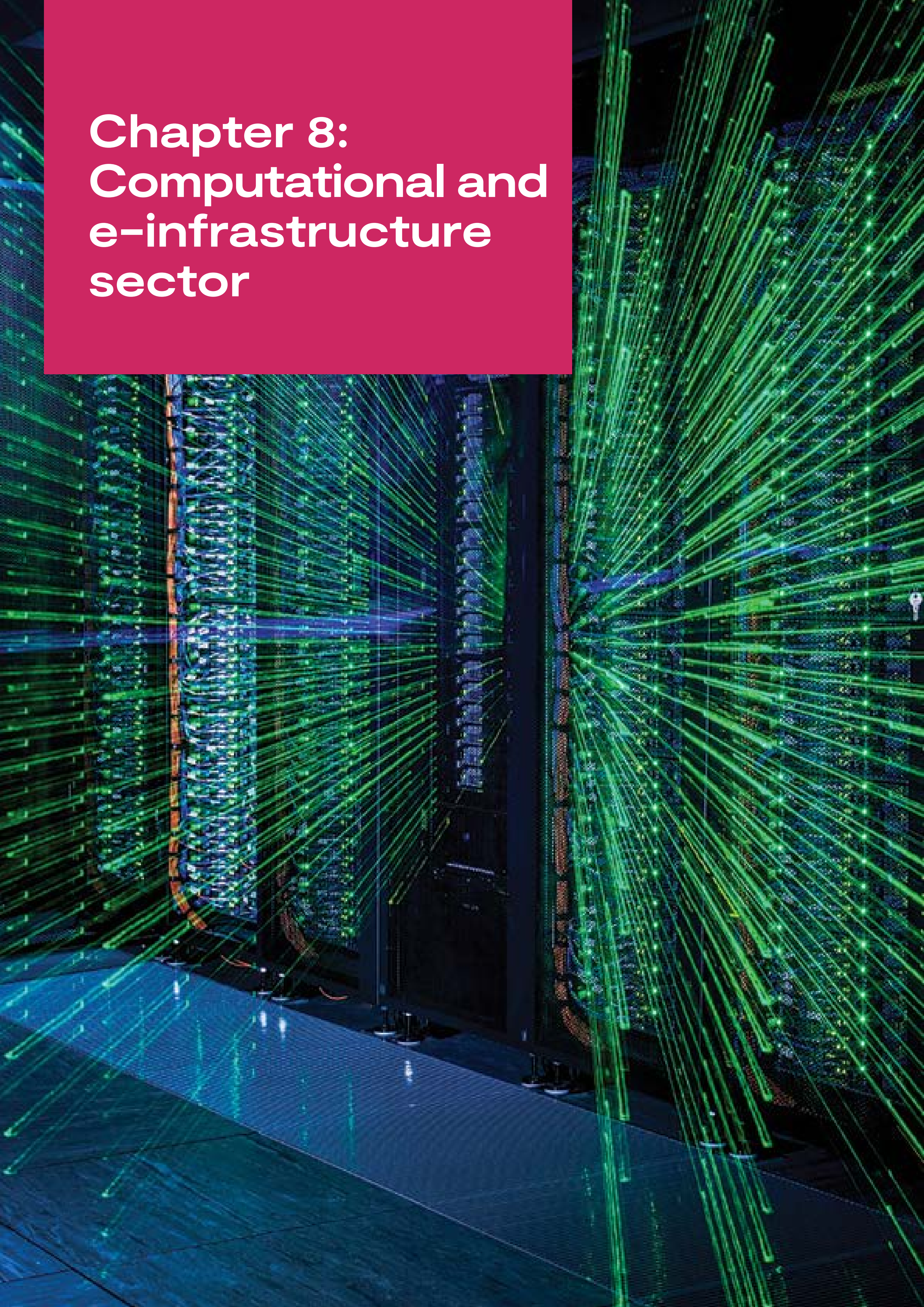
CCS, along with the parallel research area of carbon capture utilisation and storage, enables decarbonisation of fossil fuels by capturing and permanently sequestering the exhaust CO_2. CCS can also play a role in enhancing the performance of oil and gas recovery wells. CCS could assist in the production of hydrogen from natural gas by capturing and sequestering the carbon from methane, with the hydrogen then used as a clean energy vector. It has been estimated that these technologies could be applied to mitigate a significant amount of the UK's carbon emissions. The UK is strongly placed to lead in CCS technologies with significant potential for offshore storage of CO_2 in decommissioned oil and gas wells.

However, technical challenges remain. CCS is costly and not highly efficient. Estimates suggest between 25% and 30%[87] of the energy in fossil fuels would be needed to capture, transport and pump CO_2 underground, leading to an increased demand for fossil fuels. Separation technology is also not fully efficient, capturing 90%[88] of the CO_2, which means there will still be some emissions. Given these challenges there are opportunities for infrastructure to support:

- Decarbonising energy-intensive industries where alternative fuels would be difficult such as steel manufacture, or industries where CO_2 is a product of the manufacturing process such as cement production
- Studying how CO_2 would behave in a geological store as it is uncertain how long CO_2 would remain underground or how host rock would react if large volumes were to be injected

Theme 7: Carbon capture and storage	
How this area can be progressed/indicative approaches	
Research institute for decarbonising heavy industry	Consider options for a network of coordinated facilities for demonstrating next-generation capture and utilisation technologies, as well as optimising amine scrubbing, at a scale of 1–10MWe equivalent. This would act as a bridge from small pilot plants to full-scale demonstrators and could also cover emerging next-generation capture technologies at a smaller scale. These can be developed through pilot plants operating at a scale of around 50–500kWe.
Subsurface laboratory for CO_2 injection and storage	A demonstration facility with CCS as part of an integrated energy system would enable exploration of key implementation challenges. This could take the form of a 'borehole lab', with an array of boreholes, instrumentation and research capability.

Chapter 8: Computational and e-infrastructure sector



We are witnessing a revolution in research and innovation. Modern research is still founded on the basic principles of observation, experiment and theory, but computational and data analytic approaches are now central to all research sectors. Consequently, the whole UK research and innovation community is increasingly reliant on the UK's research e-infrastructure[89,90,91] (high-end computing, large-scale data storage and high-capacity data networking).

The UK's e-infrastructure needs to deliver across the research and innovation sector, for example:

- Large-scale experimental facilities such as the LHC, Diamond, the SKA and the Hinxton genomics campus will produce increasingly large volumes of complex data, requiring a corresponding increase in computational resources to maximise the benefits from the data they generate
- The mining of large and complex data sets has the potential to transform research areas; for example, earlier chapters described opportunities to generate new insights from social, historic and medical data
- Highly sophisticated computational simulation now plays a critical role in the interpretation of results in a number of fields
- The UK's e-infrastructure also underpins innovation, where the development of new products can be accelerated by combining real-world and simulation approaches[92]

E-infrastructure is now essential for almost all disciplines and research and innovation sectors. The diverse nature of applications requires a diversity of provision to meet the requirements of the different fields. It also needs to support and develop in tandem with the increasingly pervasive application of AI and machine learning, with opportunities for each technology to drive advances in each other.

8.1 Overview of current capability

The e-infrastructure sector consists of: computational resources to conduct modelling, simulation and data analysis; large-scale data storage facilities; and the network infrastructure to enable data to be stored, accessed and shared. This diverse ecosystem (Figure 17), which ranges from top-end supercomputers to smaller local capabilities, delivers the required technical diversity. Exploiting this computational hardware requires a diverse range of software tools for modelling, simulation and data analysis.

The UK's computational e-infrastructure can be broadly categorised as:

- National facilities such as Advanced Research Computing High End Resource (ARCHER), DiRAC and the Hartree Centre
- E-infrastructure at experimental facilities that support the research that facility users are carrying out
- Data facilities and resources to support specific research areas
- E-infrastructure at research centres and institutes to support their own research programmes, which may require access to the three other classes of e-infrastructure

This ecosystem provides a diverse range of resources covering high-performance, high-throughput and data-intensive computing. It also provides resources at different scales, ranging from large-scale national facilities to smaller-scale local facilities, reflecting the diverse needs of the research and innovation community. It supports both pure research needs (for example, ARCHER and DiRAC) and industry-focused innovation (for example, the Hartree Centre).

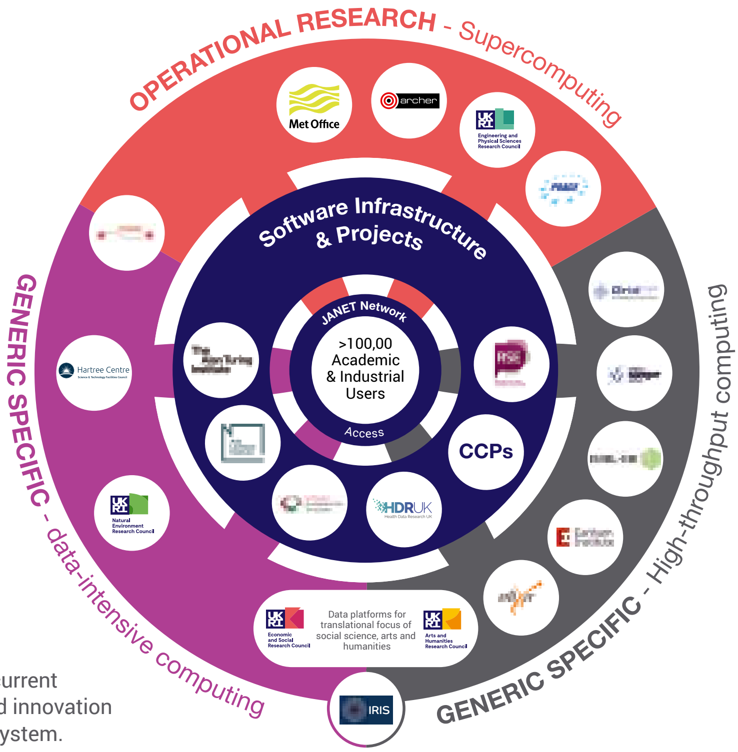


Figure 17. The UK's current national research and innovation e-infrastructure ecosystem.

CASE STUDY:
The Hartree Centre: transforming UK industry through HPC, 'big data' and cognitive technologies (AI)

The Hartree Centre is the only supercomputing centre in the UK with industrial engagement as its primary role. It was established to allow UK businesses, ranging from large corporate organisations to startups and small businesses, to benefit from the specialist expertise and access to supercomputers and other emerging technologies that would normally only be available to academic researchers[93].

Developed following significant funding from UK government, and with strategic partnerships with major industry leaders, the Hartree Centre brings together some of the most advanced systems, technologies and experts in these fields. The sectors of the economy where Hartree is generating impact include: consumer goods (32%), energy (6%), manufacturing (14%), transport (6%), chemicals (7%), ICT (14%) and other sectors (21%). In its first four years of operation, the Hartree Centre has:

- Undertaken 100 projects with commercial companies
- Carried out a further sixty-seven projects with other organisations such as the Met Office
- Delivered £27.5 million net commercial benefit to its users
- Achieved an additional £7.1 million net impact from its operational expenditure
- Delivered 130 training courses, totalling 3,760 training days

STFC / Hartree Centre

8.2 Future direction

For the UK to remain at the forefront of research and innovation will require a long-term and strategic programme of investment in e-infrastructure. This will need to address the requirements of the whole UK research and innovation community and should enable and support cross-disciplinary research. The level of ambition needs to reflect the transformative and disruptive nature of applications of computational techniques across the research and innovation sectors.

Our objectives are:

- To host a world-class national exascale supercomputing facility by the middle of the next decade
- To accelerate the development of the UK's computational and data-intensive research by providing increased capacity and capability across the e-infrastructure ecosystem
- To progress towards a more integrated e-infrastructure ecosystem by developing the tools and techniques to support it (access and security, data storage and access) and by finding opportunities for interoperability, co-location and aggregation of resources
- To nurture a cadre of highly skilled data and computationally literate professionals whose influence extends beyond academia – this is an essential for maintaining the UK's scientific leadership and to contribute to the skills base required to deliver the government's Industrial Strategy
- To support the adoption of new technology across all sectors, recognising that the leading edge of informatics technology is advancing rapidly
- To increase the ease of access to e-infrastructure resources for users from across the different research sectors and to drive innovation

UK Research and Innovation Review of Artificial Intelligence

AI and data is one of the Industrial Strategy Grand Challenges. The Dame Wendy Hall report Growing the Artificial Intelligence Industry[94] estimates exploitation of AI technologies and data assets will add £630 billion to the UK economy by 2035. UK Research and Innovation is currently undertaking a review of AI research and innovation. This review will provide a strategic analysis of the support for AI research and innovation and recommend future support strategies that will enable AI to reach its full potential in the UK. It will draw on the analysis from this programme to consider all facets of support required and look more broadly to cover the critical research and innovation challenges and skills needs that if, addressed, will enable the UK to maintain its world-leading position.

The objectives of the review are to:

- Map UK Research and Innovation's current support for AI-related research and innovation
- Engage key stakeholders in exploring the UK's ambitions and desired outcomes for AI-related research and innovation, and consider the role of public investment in delivering these
- Set the UK's current position and future potential in an international context
- Set out a strategy for appropriately supporting AI research and innovation in the UK

An advisory group chaired by Professor Tom Rodden has been established and the review will report in autumn 2019.

8.3 Future requirements and opportunities

Consultation over the course of the programme suggests the need for an ambitious plan for the development of the UK's e-infrastructure, in recognition of the **certain growth in future demand** and the importance of e-infrastructure in increasing the value and efficiency of other research and innovation infrastructure. Alongside this growth in demand, the diversity of users from academia and industry is also increasing which means the requirement for **flexibility, diversity and heterogeneity** in the system is critical.

Investment in the UK's e-infrastructure ecosystem needs to be strategic, coherent and long term. Given that major refreshes in computational infrastructure are needed on a regular cycle of three to five years, effective planning will require a **sustained multi-year investment** in the overall ecosystem. This would support a more strategic approach across the ecosystem as a whole, enhancing our ability to rapidly adopt evolving technologies and to respond to changing demands. Longer-term planning, combined with technology horizon scanning, will ensure the UK is well placed to take advantage of new technologies.

Longer-term planning is essential in the development of a coherent e-infrastructure ecosystem that provides capability at local, regional and national levels. It is also necessary for the optimal provision of sufficient capacity to meet emerging demand and to deliver services in an integrated way. For example, developing a national exascale facility by the middle of the next decade will require a number of intermediate steps in terms of hardware provision.

The effective operation of any e-infrastructure ecosystem is also dependent on the availability of the right skills and talent in universities, research institutes and business (Chapter 11). In this sector, support for **research software engineers and research data professionals** is particularly critical.

In producing this report there has been a great deal of progress in mapping the future e-infrastructure requirements of the UK's research and innovation communities. The table below summarises the main themes for the future of the UK's e-infrastructure, which will form the basis for the development of a detailed longer-term strategy. As described in Chapter 2, these are at different stages of development. Some areas need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered, whilst others are more developed and could be implemented sooner.

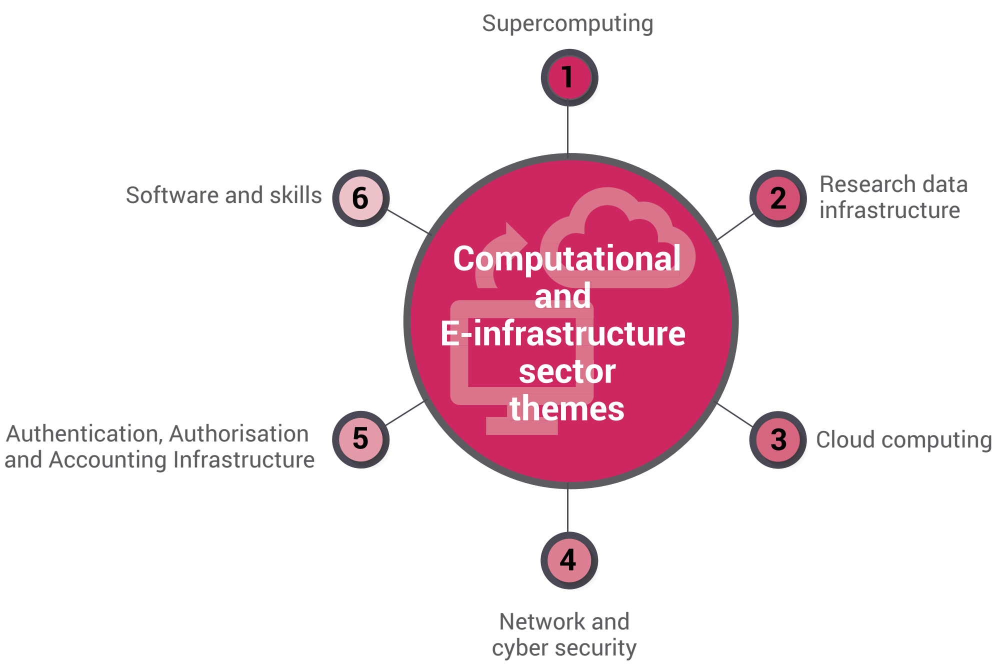


Figure 18. Computational and e-infrastructure themes overview.

Computational and e-infrastructure theme summary	
Supercomputing (HPC)	■ Top supercomputing tiers, aiming towards exascale by 2025 ■ HTC for facilities/research centres ■ Research into emerging quantum computing capabilities
Research data infrastructure: data storage and High-Throughput Computing (HTC)	■ Data centres to deal with ever-increasing capacity requirements ■ Middleware and application programming Interfaces to enable data access and analysis ■ Computational HTC resources to analyse large data sets
Research data infrastructure: research data management	■ Data management and curation services and the development of metadata infrastructure to support integration and interoperability
Cloud computing	■ Management, coordination and oversight of cloud computing for the research community ■ Support for the transition of UK Research and Innovation workloads to hybrid ecosystems by developing models and technical solutions for more cost-effective use of cloud computing
Network and cybersecurity	■ Consideration of the national network (Janet), its interconnections to other national and international networks and the connection to campuses of universities and laboratories
Authentication, Authorisation and Accounting Infrastructure (AAAI)	■ Development of access management tools to enable flexible interoperability of e-infrastructures and data resources
Software and skills	■ Support for software engineering, maintenance and product development using existing mechanisms including targeted calls ■ New software and algorithms to address emerging societal challenges, new technologies such as exascale, AI and machine learning, and the data challenges such as metadata and interoperability ■ Career development of research software engineers and research data professionals

Theme 1: Supercomputing

High-Performance Computers (HPC), often referred to as supercomputers, are computational facilities used to support research requiring calculations or simulations that are so complex that they cannot be performed elsewhere. HPC applications range from 'digital twinning' of complex engineering components, to detailed simulations of turbulent fluid flow, to the theoretical calculations of lattice quantum chromodynamics that underpin precise measurements at the LHC. Supercomputers are also being used for large-scale AI and machine learning challenges with research and innovation applications.

The current UK HPC ecosystem can be categorised into four tiers[95] (Figure 19). Tier-1 resources provide the highest-capability national research HPC machines, such as ARCHER and DiRAC. Tier-2 provides institutional training and entry-level HPC such as Peta-5 and MONSooN. Tier-3 machines mainly provide local university resources. UK researchers can also access leadership-class capability Tier-0 resources through the Partnership for Advanced Computing in Europe (PRACE)[96].

The UK's computing requirements are expanding, but the capacity available is already severely constrained. The UK is trailing its European neighbours in terms of available computing resources; it is almost a factor of two behind Italy, more than a factor of two behind Poland and more than a factor of three behind both Germany and France.

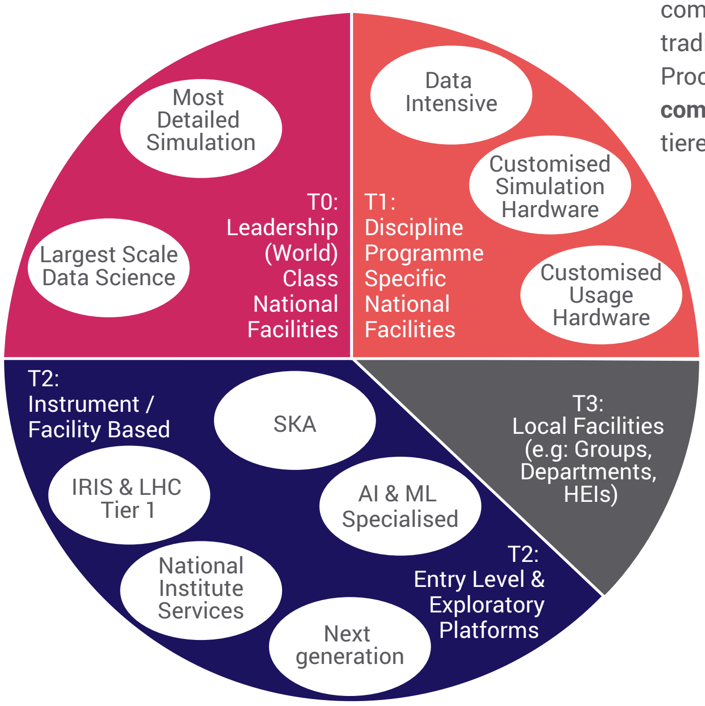


Figure 19. The components of a balanced supercomputing ecosystem
Image credit: Lawrence & Jenner.

There is emerging consensus that the UK should host a national exascale Tier-0 facility by the middle of the next decade, cementing our position at the forefront of high-end computing. This would put the UK on a path to world-class HPC capability for the next ten years:

- **Medium-term:** a UK national exascale facility
- **Short- to medium-term:** either a national pre-exascale system or access to international facilities to enable UK researchers to develop the skills necessary to utilise the potential of exascale computational architectures
- **Short-term:** refresh of existing facilities/capabilities, targeting increased coherence of approaches and hardware – this could include the provision of a new system optimised for AI/deep-learning applications

Achieving this goal and maximising the benefits to UK research and innovation will require sustained strategic investment across the tiers, supporting a well-coordinated supercomputing service including a Tier 0 scale system at the apex. Looking beyond the exascale, there is a need for research into the concept of future computational architectures combining traditional Central Processing Units, Graphics Processing Units and emerging **quantum computing capabilities**. This would build on the tiered supercomputing service described above.

Theme 1: Supercomputing	
How this area can be progressed/indicative approaches	
Leadership-class (Tier-0) national supercomputing facilities	The aim would be to meet the goal of the UK hosting an exascale system by 2025/26, in support of Grand Challenges which push the frontiers of science and innovation. A project is currently under way to scope the options including the potential to work with international partners.
Workflow-specific (Tier-1) national supercomputing facilities with distinct capabilities in support of particular types of modelling or particular communities	This would involve supporting Grand Challenges that require specialist hardware tailored to the scientific requirements. Examples include: ■ DiRAC ■ ARCHER (ARCHER2 in procurement) ■ The Met Office ■ The Hartree Centre ■ JASMIN ■ UKAEA (planning under way) ■ EMBL-EBI (phase 1 under way, planning for phase 2 in preparation)
National AI service	A national service for machine learning applications would work across UK Research and Innovation's remit and include hardware, software and service support. This has the potential to offer 'machine learning as a service'.
Tier-2	Expansion of Tier-2 facilities: entry-level and exploratory platforms would allow users to carry out larger computations relatively quickly and find out whether larger/longer projects on other platforms may be practical. Investment here would also allow exploration of new computing paradigms and provide experimental test beds for both hardware and software development.
Hosting infrastructure	Development of data centres and computer centres to host e-infrastructure facilities would need to be in place to avoid delays in installing and using supercomputer facilities.
Beyond exascale – quantum computing	There is an opportunity for additional research into the potential of future computational architectures that incorporate quantum computing accelerators. The current need is for additional research in the field but may lead to infrastructure investments in quantum computing within a few years.

Theme 2: Research data infrastructure

The diversity of data sources means that infrastructure requirements are often domain-specific and closely linked to the data collection and production process. Expert engagement over the course of this programme suggests an extremely high growth rate in data availability across all sectors. This is evident in each of the previous chapters, all of which contain options for additional data generation and collection infrastructures.

Although hard to quantify, the estimates of potential data storage requirements comfortably exceed the exabyte scale (where an exabyte is 10^{18} bytes). For example, the GAIA all-sky survey database is set to become one of the first petabyte-scale (10^{15} bytes) databases with data from over 2 billion stars in our galaxy. In the healthcare sector, increased precision imaging and digitisation of healthcare records are expected to drive international healthcare data volumes to 17.1 exabytes by 2020. By 2030, estimates of global patient data of 800 exabytes seem plausible, with the UK component estimated to be about 7% (60 exabytes).

This projected rapid increase in data volume presents challenges in terms of both data storage provision and the required rapid growth in computational resources for analysis. These HTC resources will need to be scaled to meet the challenges presented by large-scale facilities (such as the High-Luminosity LHC, the SKA and Diamond) and the needs of the biomedical and social sciences. At this stage, it is not possible to present a detailed assessment of likely future needs but it is clear that sustained investment is required to exploit existing and future infrastructures. **A more detailed roadmap for the development of research and innovation data infrastructure over the longer term is a priority.**

CASE STUDY:
ELIXIR a distributed infrastructure for life science information

ELIXIR brings together life science data resources from twenty-two members located in twenty-one countries across Europe and EMBL, to manage and safeguard data through databases, software tools, cloud storage and computing facilities and training opportunities. ELIXIR enables the life sciences to derive maximum knowledge and understanding from biological, medical and environmental 'Big data'.

ELIXIR brings experts together to tackle challenges with far-reaching impacts, e.g. resource interoperability, secure access to human data, and scalable genomics. For example, the Human Protein Atlas is used 1.2 million times per year by scientists from 198 countries. ELIXIR is organised as national nodes and hub (hosted by EMBL-EBI within the Wellcome Genome Campus, which is also represented as a node). The UK node (of fifteen organisations) unites UK experts and resources in bioinformatics and computational biology at a national level.

skeeze from Pixabay

Theme 2: Research data infrastructure	
How this area can be progressed/indicative approaches	
Data storage and HTC: short-term	Provision of data storage and HTC resources is needed to exploit existing infrastructures and those coming online in the near future.
Longer-term planning	Develop a roadmap for UK research and innovation data infrastructure (storage and computational resources) taking into account the projected needs of all sectors. This should consider: ■ **Access and analysis infrastructure:** requirements for physical storage, HTC for analysis and the software tools ('middleware') to enable access and analysis ■ **Research data management or 'stewardship' infrastructure,** including the software tools for curation and management, and skills required ■ **Opportunities for sharing and co-location**

Many HEIs and research and innovation organisations have their own dedicated data infrastructures that provide data storage and access. Mechanisms to support and fund data infrastructures also exist across UK Research and Innovation. These include support for UK Research and Innovation Council-focused repositories and designated funding schemes that can be used to support innovative software and analytics, for example the BBSRC Bioinformatics and Biological Resources Fund. There are strong opportunities for sharing best practice in data management, processing, curation, analysis and knowledge generation; the implementation of FAIR (Findable, Accessible, Interoperable, Reusable) principles; and identifying opportunities for sharing or co-location. This requires strategic coordination in order to ensure appropriate integration and federation.

Theme 3: Cloud computing

Cloud computing has brought about a fundamental shift across many sectors in the way e-infrastructure is provisioned and accessed. Researchers and innovators need to be able to access the most appropriate computing solutions. Both cloud computing and more traditional approaches are likely to be needed to address the data challenges highlighted in Theme 2 above. The balance between the different approaches needs to be informed by practical and commercial considerations.

Theme 3: Cloud computing	
How this area can be progressed/indicative approaches	
Cloud computing strategy	Development of a clear cloud computing strategy is critical to support best practice use of cloud across the research and innovation community and to ensure we make the most of the opportunity that cloud provides.

Theme 4: Network and cybersecurity infrastructure

A seamless and reliable service requires a series of interconnected networks involving a complex ecosystem of technical standards and operating agreements and underpinned by telecommunications infrastructure of appropriate capability, capacity and geographical reach. This requires consideration of the national network (Janet), its interconnections to other national and international networks, and the connection to campuses of universities and laboratories.

These networks need to remain competitive and responsive to the changing nature and levels of user demand. As well as directly enabling data access and analysis for the wider research community, they indirectly support collaboration and sharing. They also need to be able to detect, protect and mitigate the rising level of cyber threats to infrastructure, confidentiality and integrity of research data.

Theme 4: Network and cybersecurity infrastructure	
How this area can be progressed/indicative approaches	
Janet and campus networks	A multi-year programme of investment in the network and cybersecurity would build further capability in campus networks and nationally. This could be achieved through a series of capacity upgrades until 2028 when the current contract ends and would provide the transmission infrastructure to move data at scale, reliably and with international reach.

Theme 5: Authentication, Authorisation and Accounting Infrastructure (AAAI)

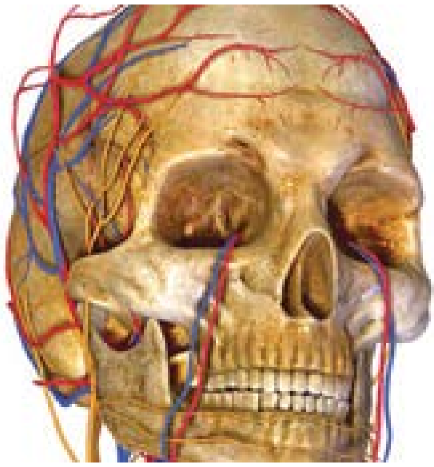
AAAI is a key enabler of federating e-infrastructures in a flexible and responsive way. It is a framework for intelligently facilitating reliable, seamless and transparent access to potentially high-volume, geographically distributed and complex data with many owners for researchers who wish to share and work collaboratively and in a secure manner. A common AAAI framework will allow researchers and innovators to access the resources they need and are permitted to use more easily. It includes services to facilitate secure access to data that can only be made available through a secure environment. Benefits of a national AAAI include increased sharing and reuse of data between different research disciplines, increased access to international resources, improved researcher experience, lower integration and operational cost and increased security of data and resource.

Theme 5: Authentication, Authorisation and Accounting Infrastructure (AAAI)	
How this area can be progressed/indicative approaches	
AAAI	The development of a national AAAI would facilitate reliable, seamless and transparent access to potentially high-volume, geographically distributed and complex data with many owners for distributed and varied researchers who wish to work collaboratively and in a secure manner. There are existing islands of AAAI and work is needed to create and implement a common framework.

CASE STUDY:
Improving neurosurgery through HPC and novel software

University College London researchers are collaborating with Allinea Software to develop software that models blood flow within the cranium, the part of the skull that encloses the brain, using data generated by an MRI scan.

This improves our understanding of blood pressure near points of weakness such as aneurysms, which in turn improves treatment of patients. The software has undergone extensive development using the national HPC service, ARCHER, to enable the study of the Circle of Willis (a network of blood vessels in the brain) for very first time.



Theme 6: Software and skills

Software lies at the heart of many research and innovation activities. It is needed to control the instrumentation to record data. It is used for the complex modelling required to understand cell function, fusion reactions and the climate. It is the enabling technology behind major advances such as decoding the human genome and the discovery of the Higgs boson and it lies at the heart of strategically important technologies such as AI. Software can be a few lines of code written by a single researcher or a major framework developed over decades by dedicated teams of researchers and software engineers. In academia, 92% of UK researchers use research software and 69% report that it is fundamental to their research with software development a research activity in its own right. The near-ubiquity of software means that it is not possible to disentangle the quality of the software from the quality of the research. Unreliable and untested software leads to unreliable results that cannot be trusted.

The development of a clear strategy for software with support for high-quality software development and strong policies to support best practice is a critical part of the future landscape. Such a strategy would provide an important strategic framework for the options set out below.

Theme 6: Software and skills

How this area can be progressed/indicative approaches

Software to support future research and societal challenges	Targeted funding could support: ■ Software to accelerate progress on key research challenges ■ Forward-looking activities exploring the software implications and opportunities of step-changes in computing hardware ■ Software infrastructure that enables interoperability between data collections and improves metadata enrichment and effective use of data
Software maintenance	A programme supporting maintenance and development of existing software would enable the full value to be extracted from software throughout its lifetime. This could be based on existing funding mechanisms.
Software communities of practice	This could involve support for mechanisms such as collaborative computational projects, consortia and the Computational Science Centre for Research Communities.

The development of software and the support of the UK's e-infrastructure relies heavily on skilled researchers. If the UK is to meet the ambition of remaining at the forefront of computational and data-intensive science, the career development of research software engineers and research data professionals is critical. These professionals also have important roles in teaching and training at both undergraduate and graduate level and may be based in universities, research institutes or businesses.

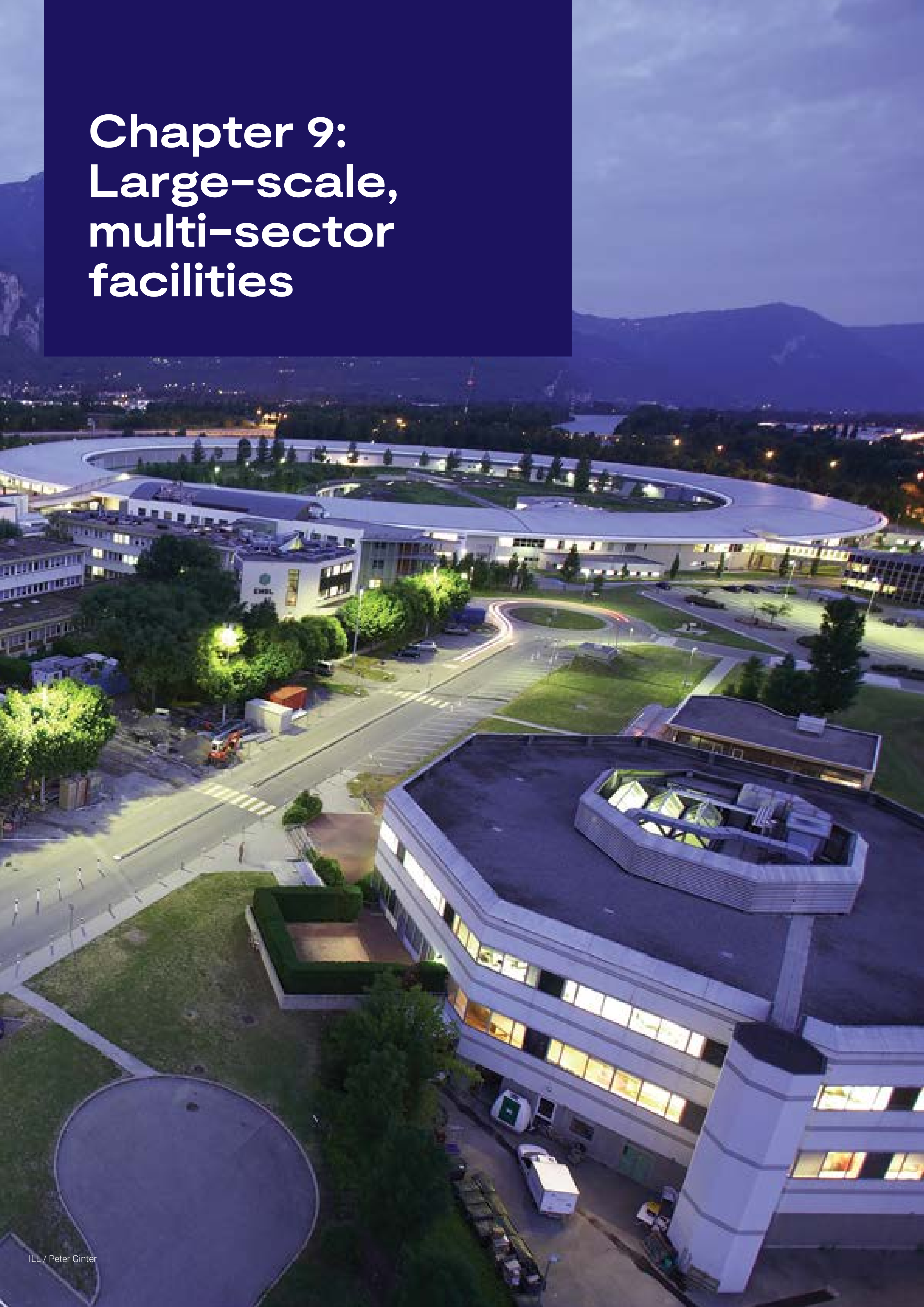
Until recently, the career paths for software engineers and research data professionals within academia had not been well defined. These skill sets are already in high demand across both industry and academia, so it is critical that the UK provides the environment to nurture and retain these highly skilled individuals.

Future needs could be addressed through existing mechanisms or through the creation of a national network of facilities for research software engineering, which could help broker access to these skills across the UK. Investment in business engagement and development of skills would also enable enhanced collaboration with industry. The skills required, which are summarised in the table below, are wider than just those of research software engineers and research data professionals.

Example roles and functions needed for an effective operational UK e-infrastructure system

Expertise	Function
Research software engineering	Develop software applications for deployment.
Research operations engineering	Build, test, configure and release/deploy services. Operational interface between the scientist/researcher and the deployed environment.
Network engineering	Manage on-premise network infrastructure and cloud connectivity.
Data engineering and wrangling	Design, build and manage the information infrastructure. Transform and map data from one 'raw' format into another.
Data analysis and data mining	Discover patterns in large data sets with the goal of discovering useful information, informing conclusions and supporting decision-making.
Data curation, stewardship and management	Acquisition and curation of information from one or more sources and the use of tools to curate data for different analytical tasks.
Information security and governance	Manage information at an organisation, balancing the use and security of information. Legal compliance, operational transparency.

Chapter 9: Large-scale, multi-sector facilities



ILL / Peter Ginter

Addressing the challenges faced by UK businesses and policy-makers requires research and innovation within and across traditional disciplines and boundaries. Infrastructure can play a unique role in bringing together different combinations of expertise to address complex problems and foster the sharing of knowhow. This chapter focuses on large-scale, multi-sector facilities that are established with the intention to serve a wide multitude of sectors.

Our analysis of the current UK landscape shows how **92% of infrastructures already work across more than one sector** and many provide underpinning capability to support a diverse array of projects and programmes. Working across disciplines and sectors is both important and challenging. Stakeholders have commented throughout this programme on both the benefits and the barriers to inter- and multidisciplinary working. Shared goals and use of common facilities can lead to new collaborations and demonstrate the benefits of diverse expertise. Fostering a collaborative culture is critical but often requires proactive support to develop the necessary behaviours, structures and practices.

Investing in research to develop new methods and technologies is a critical component of the fundamental discovery work UK Research and Innovation supports and there are **opportunities to foster innovation by using the expertise developed in one discipline in new contexts.** Infrastructures can act as a test bed for prototyping and developing the next-generation of instrumentation by working with potential suppliers, leading to new business opportunities. They can also foster innovation in methodologies to inform the next-generation of infrastructure investments. This is facilitated by the ability of the expert staff at infrastructures to work with multiple types of user from academia and business.

This chapter focuses on the large-scale, multi-sector facilities that are established with the intention of serving a wide multitude of sectors. The UK has a strong track record in establishing and operating such facilities which often operate for many decades, take many years of planning and are technically complex, necessitating delivery through national- and international-scale collaborations. They are designed to support users from across academia and business sectors, with skilled technical staff working closely with visiting researchers as well as undertaking in-house research and innovation. Cross-fertilisation of ideas is stimulated at such facilities where users bring a variety of research questions and innovation challenges.

These facilities are dedicated to characterising and imaging the molecular and atomic structures of inorganic and biological materials using a range of technologies such as synchrotrons, conventional and Free Electron Lasers (FELs), X-rays, neutron reactors or spallation sources. This detailed characterisation has proved important in the development of new pharmaceutical products, provided chemical analysis to improve fuel delivery efficiency in engines and revealed the structures of molecules that in turn have helped generate new treatments for cancers[8].

CASE STUDY:
Boulby Underground Laboratory

The STFC Boulby Underground Laboratory is the only deep underground science facility in the UK. Located on the edge of the North Yorkshire Moors, the laboratory is housed within the tunnels of a working polyhalite and rock-salt mine. 1,100m of rock overhead shields the laboratory from the natural cosmic rays which bombard the Earth's surface, and the surrounding rock salt is low in natural background radioactivity. This makes Boulby the ideal location for low-background particle physics experiments as well as other projects requiring access to the scientifically interesting deep underground environment. Studies under way at Boulby range from neutrino studies and the search for the dark matter in the Universe to studies of geology, geophysics and biology in extreme environments and technology development for mining and planetary exploration.

Sean Paling, Director of Boulby Underground Laboratory, STFC.

9.1 Overview of current capability

The UK is a partner in many international facilities including the Institut Max von Laue – Paul Langevin (ILL), the European Spallation Source (ESS), the European X-ray Free-Electron Laser Facility (European XFEL) and the European Synchrotron Radiation Facility (ESRF). The UK's national large-scale multidisciplinary facilities are based at the Rutherford Appleton Laboratory (RAL) on the Harwell Campus, including Diamond, the Central Laser Facility (CLF) and the ISIS Neutron and Muon Source (ISIS). This co-location at the Harwell Campus allows cross-fertilisation of ideas that can lead to new products, services and business opportunities (Chapter 10). These facilities support research and innovation across sectors as indicated in the following table. The connection to the wider research and innovation base, including the life sciences, is enhanced by the Research Complex at Harwell (RCaH) and the Rosalind Franklin Institute, which is under construction. For example, RCaH houses CLF lasers, imaging equipment and equipment for preparing samples that have short lifetimes or cannot travel great distances.

Examples of the cross-sectoral reach of the UK's large-scale, multi-sector facilities:

Facility	Biological sciences, health and food	Physical sciences and engineering	Social sciences, arts and humanities	Environment	Energy
CLF	Imaging biological samples	Understanding astrophysical objects and processes	Analysis of ancient human remains	Understanding cloud chemistry	Laser-driven fusion
Boulby Underground Laboratory	Impact of low-radiation environments on organisms	Dark matter experiments		Geology/ geophysics studies	Muon tomography for CCS applications
Diamond/ ESRF	Understanding and tackling the origins of disease and ageing	Accelerating the discovery of new materials and manufacturing processes	Study and preservation of old-master paintings and archaeological finds	Studies into the impact of air pollution on climate change	Sustainable solutions for pollution from plastics and for car exhaust design
European XFEL	Analysing the structure of biomolecules	Research into better catalysts for industry		Studying natural photosynthesis processes	Solar cell and fuel cell energy research
ESS/ILL/ISIS Neutron and Muon Source	Developing improved antiviral drugs	Investigating materials and fabrication processes for space and aerospace applications	Analysis of archaeological artefacts	Studies into air and water pollution	Materials / technologies for energy generation and storage (e.g. batteries, fuel cells)

Experiments run at these infrastructures typically produce huge volumes of data and the storage of, processing of and access to such data are a vital part of the infrastructure landscape. Many of the large facilities require dedicated and specialised e-infrastructure to support their data storage and analysis.

9.2 Future direction

The nature of these large-scale facilities means the UK operates as part of a global network and any coherent plan for UK facilities must also take account of international developments. **Supporting the next-generation of large-scale, multidisciplinary infrastructures** such as light sources, electron tomography, FELs, neutron sources and intense laser sources is an important element of the UK research and innovation landscape and there is the potential for the UK to host a new international facility. **Upgrades to existing multidisciplinary facilities,** such as the European Synchrotron Radiation Facility-Extremely Brilliant Source, can also lead to step-changes in capability and are important to ensure our facilities can collectively continue to support a broad spectrum of evolving research needs.

The increasing complexity of these infrastructures, the large data outputs, the challenging and extreme environments and the multidisciplinary nature of the problems they address make **continuous technical advancement** particularly important. This improves the capability of the facility; for example, automation of sample preparation areas significantly improves the efficiency of processing, allowing greater throughput and improved access.

Working in partnership with users: it is critical to ensure the right infrastructures are being utilised for the right research. Infrastructure staff working alongside and in partnership with users rather than as a 'service provider' can ensure the best use of their capability and ensure research quality. Regular competitive reviews of the quality of the research, drawing on international expertise, are an essential part of this process.

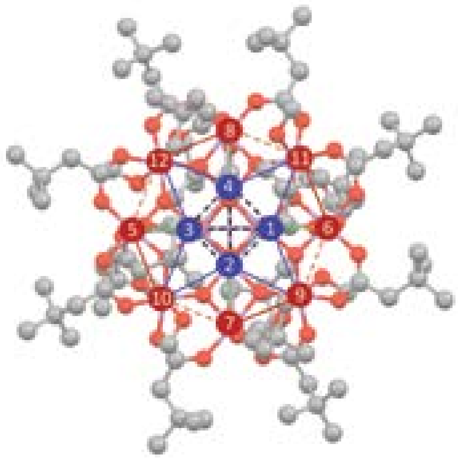
Facilitating the links between large, centralised facilities and local capability could result in greater productivity and new areas of scientific discovery (Chapter 10). In some areas, the ability

CASE STUDY:
Lowering the barriers to neutron application

The ISIS-Data Analysis as a Service (IDAaaS) computer architecture enables users of the ISIS Neutron and Muon facility to quickly and simply analyse large data sets produced by experiments. The IDAaaS technology provides powerful computing resources, software tools and data storage via an easy-to-use interface[97].

Data analysis has historically been a major barrier to maximising outputs from large research facilities, with users unable to store or process their data effectively. The running costs of each ISIS instrument are as much as £11,000 per day so it is important that users can make the best use of their time on the instruments.

For example, researchers have used the ISIS Neutron and Muon Source to characterise magnetic interactions in single-molecule magnets as part of their work to chemically design new molecules. Being able to design molecules with desired magnetic properties could enable future data storage technologies and enhance quantum computing developments[97]. IDAaaS is critical to this kind of research, allowing the researchers direct access to their data and the ability to analyse it without the need to invest in their own specialised technology, software and large personal storage space.



Tatiana Guidi (ISIS).

to do precursor studies, analyses and sample preparation prior to accessing the large facilities would be beneficial. A good example of how a national research facility can help to bridge the gap to the large facilities is the work of the UK National Crystallography Service alongside Diamond's small-molecule single-crystal diffraction beamline[98,99]. This allows the user to have access to the right tool for the right sample at the right time, making more productive use of staff and facility time.

This report focuses on opportunities for step-changes in capability through new infrastructures or major upgrades to existing capability. However, it is also **important to maintain existing facilities** so they can continue to serve their large community of researchers from the UK and overseas.

Developing improved sample delivery and more automated AI-enabled analysis would allow more users to get more useful data. For example, the development of operando experiments at Diamond that are carried out by scientists based at the nearby catalysis hub at the RCaH. Embedding R&D in sample preparation environments at large facilities also facilitates efficient use and allows sharing of good practice between the facilities and new users.

Skills and training: running training programmes alongside the operation of multidisciplinary infrastructures provides concentrated learning opportunities for new users to develop expertise quickly, share best practice and gain an understanding of the techniques firsthand. For example, Diamond and some of its industrial and university users have invested in joint appointments.

Tensioning development, operation and decommissioning of infrastructures is a challenge for all sectors (Chapter 10) but is particularly relevant for the large-scale, multidisciplinary facilities due to their scale, longevity and the often high costs associated with decommissioning. For example, the UK currently faces challenges to accommodate the cost of decommissioning of older infrastructures where that process is itself a major undertaking over many years.

9.3 Future requirements and opportunities

STFC, as the host of the UK national, large-scale, multidisciplinary facilities is currently preparing a phased roadmap for the development of current and future national facilities. The short term would see the construction of EPAC, the medium term could focus on Diamond-II and the ISIS Neutron and Muon Source Endeavour programme, with the possible longer-term focus being on a UK-FEL and the successor to ISIS. International facilities will also require long-term upgrade plans to ensure they are maintained to the highest possible standards and continue to push the boundaries of the science they support.

Although the construction phase for any upgrade or new facility project may be many years away (construction for the successor to ISIS may not begin before 2030), the technical challenges associated with their design and construction also require significant R&D many years in advance. For example, the initial R&D to explore technical options for the Diamond-II upgrade started in 2014, ten years ahead of any likely construction starting.

The following tables set out potential future requirements for both major upgrades to our existing large-scale facilities and options for new capability, building on feedback received since the publication of the Progress Report. These are at different stages of development. Some opportunities need further work to better understand the requirement, strategic importance, support within the community and ability to be delivered, whilst others are more developed and could be implemented sooner.

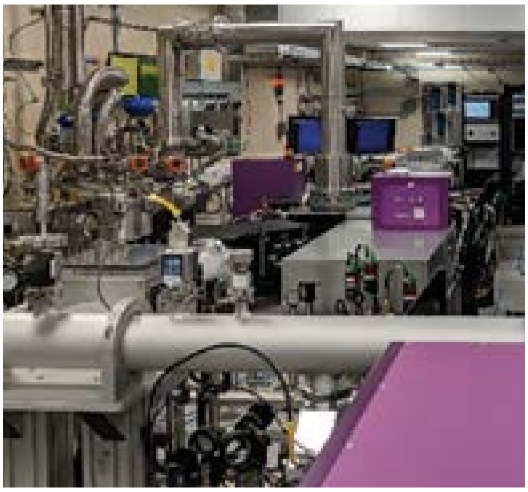
Theme 1: Next-generation large-scale, multidisciplinary facilities

The ability to analyse complex structures in more detail and over time is increasingly important across a variety of disciplines. We need to invest in a variety of capabilities including both major upgrades and new infrastructures that may include synchrotrons, lasers, FELs, X-rays, neutron reactors or spallation sources. This will likely require UK participation in flagship, international projects as well as provision of national capabilities. There are many options for the UK to consider in this area such as the opportunity to invest in fourth generation synchrotrons or the next-generation of lasers. Many of these options will also open doors to potential commercialisation of technologies invented as part of their development.

In some cases, in order to provide a cost-effective solution to capability provision, sunsetting of activities may need to be considered. Tensioning across the capabilities on offer is also often needed and should influence the investment options considered. Monitoring of benefits and continual appraisal of new and existing infrastructures will allow transparent decision-making across the portfolio.

CASE STUDY: Exporting laser technologies

The Diode Pumped Optical Laser for Experiments (DiPOLE) laser developed and built by the CLF is being exported to facilities across Europe including the billion Euro XFEL facility and the Czech Republic's HiLASE project. The revolutionary concept devised at the CLF's Centre for Advanced Laser Technology and Applications (CALTA) allows pump-probing techniques to be employed before samples are examined by an X-ray laser beam, allowing analysis of matter in extreme states. The laser's component parts are designed, predominantly manufactured and demonstrated in the UK. Roll-Royce is collaborating with CLF to find out if the DiPOLE laser could be effective for driving an optimized residual stress profile deep beneath the surface to maximize the lifetime of core component engine parts in service.



CLF

The pioneering DiPOLE D100-X laser system, developed by CLF, under final test prior to its shipment to the European X-ray Free Electron Laser (European XFEL) Facility in Hamburg, Germany.

Theme 1: Next-generation large-scale multidisciplinary infrastructures	
How this area can be progressed/indicative approaches	
ISIS Endeavour	Endeavour is a portfolio of neutron and muon instruments optimised to deliver significant and transformative impact. Development of a suite of instruments would support neutron and muon capabilities at ISIS Neutron and Muon Source enabling: transformation in future materials; smart, flexible and clean energy technologies; advanced manufacturing; and advances in biosciences and healthcare. The experimental capabilities could support the missions of the Faraday Battery Challenge, the Henry Royce Institute and the Rosalind Franklin Institute and complement capabilities at Diamond. The Endeavour portfolio together with the expertise of ISIS Neutron and Muon Source staff and the UK user community would maintain and enhance the UK's competitiveness.
High-power laser facilities	We would deliver a globally unique capability of high-powered lasers using a range of new technologies to fulfil the needs of the UK scientific community. Further work is needed to scope the precise details of a forward programme, but there are a number of potential opportunities including a national investment in Vulcan 2020 – an upgrade to the existing infrastructure delivering a twenty-fold increase in power and other related capability, and options for UK involvement in other international capabilities (including ELI).
Diamond-II	A major upgrade to Diamond would increase brightness and coherent flux at higher energies and deliver a step-change in the current capabilities at the UK's synchrotron, keeping it competitive with international facilities such as the ESRF. Strongly enhanced horizontal emittance of the electron beam would lead to a dramatic increase in the brilliance and coherence fraction of the photon beam and could create significant opportunities for a number of branches of applied science (e.g. the design and optimisation of materials and pharmaceuticals). Such technical upgrades could collectively offer orders of magnitude improvement in resolution in time and space for imaging and tomography, incorporating spectroscopic (high-sensitivity, chemically specific) information and could support missions of the Faraday Institution and the Rosalind Franklin Institute. A science case has been developed with support from the Diamond community and an independent review of the feasibility of the machine upgrade has been undertaken with international experts.
HiLUX (ultrafast structure and dynamics at RCaH)	HiLUX is an instrument development programme for the Ultra and Artemis lasers at the RCaH to create a unique centre for ultrafast vibrational, electronic and extreme ultraviolet spectroscopy and imaging. The facility would correlate the ultrafast dynamic interactions between electrons and nuclei and explore the role this has in relation to structure and dynamics in chemistry, physics and biology at the quantum level. Core applications include energy, catalysis and healthcare. A user community consultation could confirm the science need.

How this area can be progressed/indicative approaches	
Free Electron Lasers (FEL)	A national FEL facility would enable a wide range of research in the life, material and physical sciences. We will update the FEL science case in light of experience with currently operating FELs and other capabilities. The outcomes of this process will determine next steps. A decision will be made in mid-2020. Future options could include a test-bed as part of conceptual design, should a decision to work towards constructing a UK FEL be made.
Successor to ISIS	A successor facility to ISIS Neutron and Muon Source would fulfil the European need for neutrons when other facilities are closing. According to the ESFRI Physical Sciences and Engineering Strategy Working Group there could be a 'neutron drought' in Europe and the group recommends that, for Europe to equate to the US and Japanese short-pulse neutron sources (SNS and J-PARC, the most cost-effective solution would be to build a MW-class short pulse facility at ISIS Neutron and Muon Source. This would-be complementary to ESS and provide enhanced neutron capacity in Europe beyond 2030.

Theme 2: Maximising our investments in multidisciplinary facilities

The potential of existing large-scale, multidisciplinary facilities could be enhanced by step-changes in technologies and increasing connectivity between infrastructures.

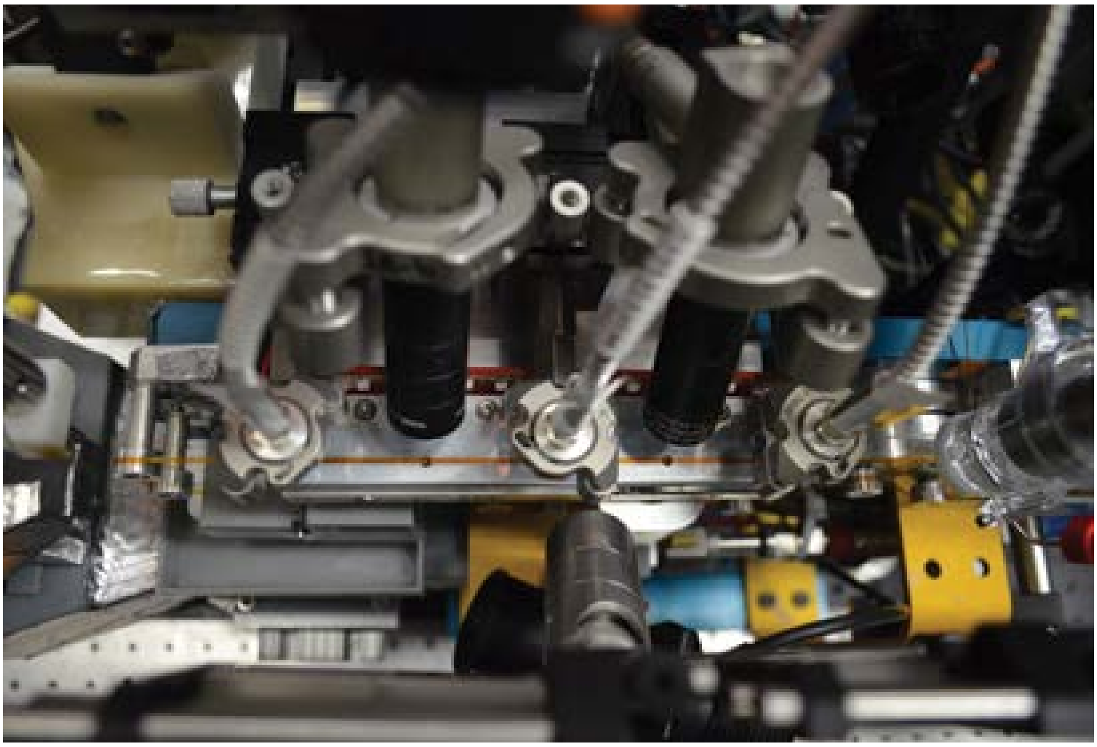
Development of smaller infrastructures which provide additional capacity would also allow the larger, more expensive capabilities to focus on the research where their unique capabilities are most essential.

Theme 2: Maximising our investments in multidisciplinary facilities	
How this area can be progressed/indicative approaches	
Imaging at the Harwell Campus	The Harwell Campus is already a centre of excellence in imaging and associated underpinning technologies, but the infrastructure and expertise is currently dispersed across various facilities and technology departments. A coordinated approach to developing new imaging technologies for the Harwell facilities, including correlative imaging, would provide the UK with a world-leading capability for imaging and enable transformational advances across the life and physical sciences.
UK platform for experimental data analysis	There is an increasing gap developing between our ability to experimentally take measurements (on large-scale infrastructures through to medium-scale facilities) and then to be able to thoroughly analyse them, i.e. we can 'measure lots and analyse little'. Creation of a new platform would support data collection and use at full potential. With increasing data production, it is important to be able to make the most efficient and effective use of these outputs and maximise the potential of our investments. Specialised data-handling mechanisms and people skills would produce tools that can increase access to and usage of the huge volume of data produced at large facilities and therefore increase cost-efficiency.

CASE STUDY:
UK-XFEL Life Sciences hub – bridging the gap to European facilities

The UK is a world leader in protein crystallography, a technique that has revolutionised biology. It has led to effective treatments for HIV, new antibiotics, new vaccines (including progress on foot-and-mouth disease), several Nobel Prizes and with the breakthrough in the structure of G protein-coupled receptors, whole new families of medicines. XFELs can be used for protein crystallography by allowing structures to be determined from nanocrystals just a few unit cells across.

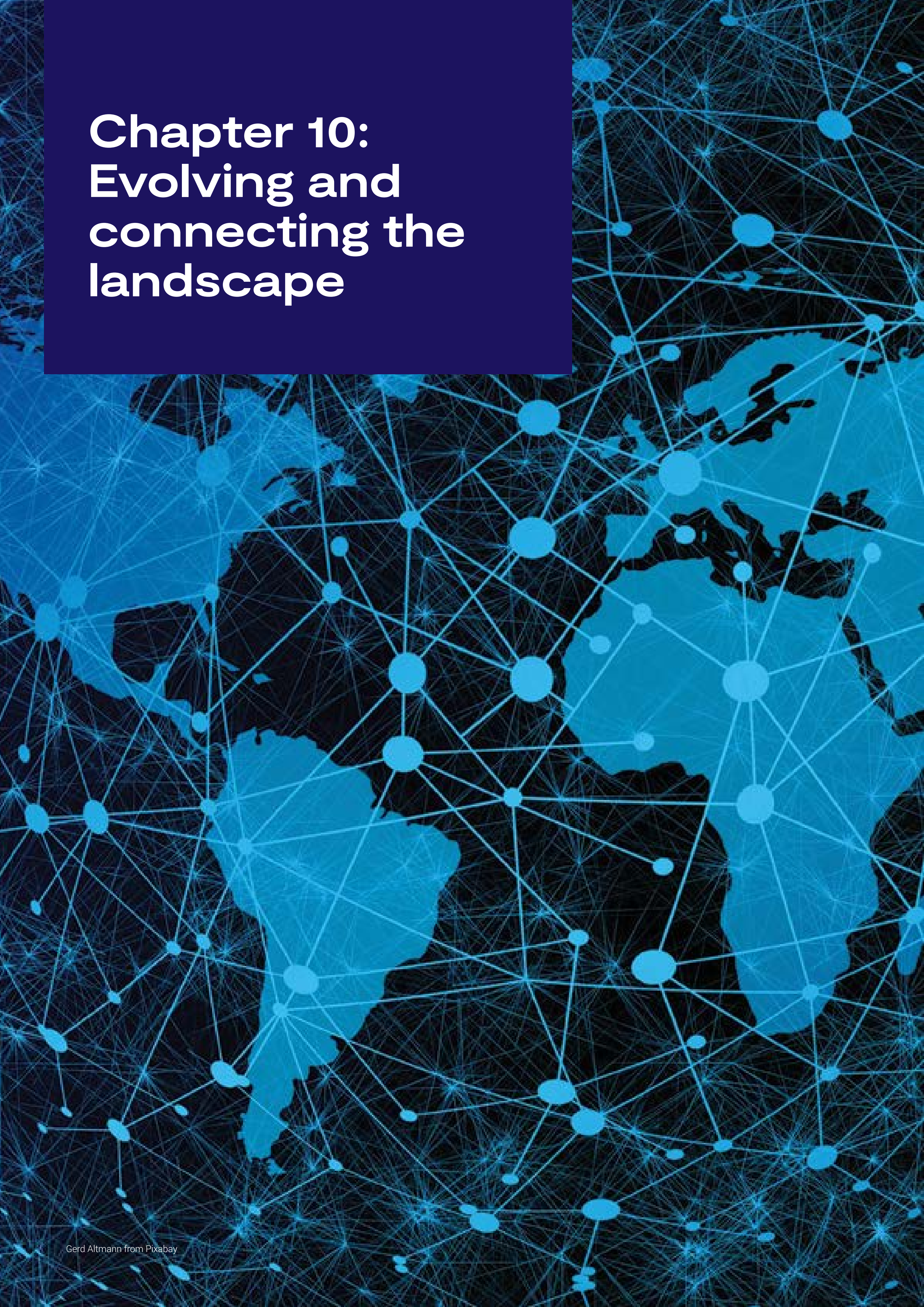
UK-XFEL Life Sciences Hub based at Diamond helps the UK research community build the required expertise to use structural biology facilities at the European XFEL in Hamburg. In-house experts work with researchers preparing to run experiments at the European XFEL, for example providing training and making sure experimental samples are suitable and flight-ready before sending them off for transit. There are plans for a dedicated fibre-optic link from Hamburg to the Harwell Campus which will allow researchers to carry out data analysis back in the UK. This would maximise use of the allocated time at the international facility.



Allen M. Orville

Close up of some of the apparatus for the laser illumination of samples at the LCLS/MFX instrument.

Chapter 10: Evolving and connecting the landscape



Gerd Altmann from Pixabay

Building and enhancing connections between infrastructures supports cross-sectoral working and more productive and efficient use of our collective capability. Many challenges or questions can only be addressed by bringing together unique combinations of partners and expertise from across academia, business, government and nations. Our aim is to build a more connected landscape and enhance our capability through partnership-working at all scales.

The sector chapters have already described how parts of the landscape are well connected but this connectivity is not consistent and so there is the scope to more fully exploit our collective potential. Connectivity is important at all scales, from localised clusters to global collaborations. It can be fostered in many ways by funders and influencers, e.g. through the use of networks, formal partnerships and collaborations, strategic investment and training of staff (Figure 20).

However, success also requires a proactive research and innovation community able and ready to take on any opportunities available. What works is tightly linked to the lifecycle of an infrastructure, the culture of different research or business communities and the maturity of the research field. Any step-change in connectivity requires support alongside the core investment in the infrastructures themselves.

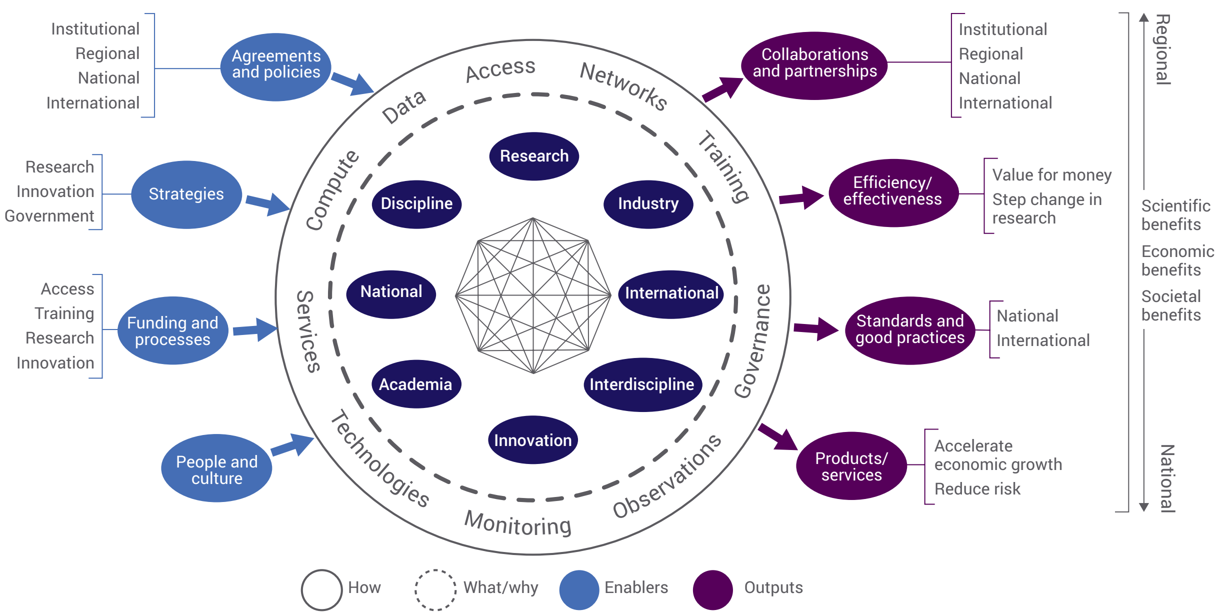


Figure 20. Levers for enhancing connectivity across the infrastructure landscape.

10.1 International collaboration

The Smith Review is a timely reminder that research and innovation are international endeavours. The UK has a long history of international collaboration benefitting from and ensuring the sharing of knowledge, expertise, data and capability across organisations, borders and continents. Many infrastructures are too big, complex or expensive for a single country to build and manage alone and their creation requires strong partnerships between governments as well as academia. The UK is a partner or leader in numerous ESFRI research infrastructures and is involved in just under half of the eighteen ESFRI projects (preparatory phase) and three quarters of the thirty-seven landmarks (implementation phase). The ESFRI Roadmap[29] demonstrates the strong commitment of the UK to ESFRI research infrastructures, with the UK being a prospective member in three of the six new projects. The UK is also an active member of the Group of Senior Officials, established by the G8 Science Ministers in 2008 to informally explore cooperation opportunities in global research infrastructures.

CASE STUDY:
Square Kilometre Array (SKA)

The SKA will be the world's largest and most sensitive radio telescope array, with its headquarters at Jodrell Bank, Manchester and facilities in South Africa and Western Australia. Once operational in the mid-2020s, it will investigate the development of the early Universe and provide insight on dark matter and dark energy. Scientists and engineers are designing and developing a system which will require network technology that will generate more data traffic than the entire internet. As one of the largest scientific endeavours in history, the SKA brings together a wealth of the world's finest scientists, engineers and policy- makers to bring the project to fruition.


SKA Organisation

The founding treaty was signed on 12th March 2019, confirming the UK (Jodrell Bank) as the global headquarters and facilities in South Africa and Western Australia. Whilst ten member countries, including the UK, are the cornerstone of the project, around 100 organisations across about twenty countries are participating in the overall design and development.

The future landscape will require further alignment of strategies amongst national governments to create and stimulate effective interconnections and drive further co-design and joint international investments in infrastructures. The Smith Review highlights the importance of enhancing collaboration and previous chapters have set out multiple **opportunities for UK participation or hosting of international infrastructures**, for example in bioimaging and structural biology and 'omics technologies' (p29), new telescopes and nuclear physics facilities (p51), heritage science (p84), data infrastructures (p71) and access to international large-scale multi-sector facilities (Chapter 9, Section 9.2). In doing this, it will be important to maintain and enhance our ability to attract infrastructure activity and skills into the UK. The government's International Research and Innovation Strategy[100] highlights the importance of global cooperation and includes leading UK and international facilities as a cornerstone of future requirements and investment. The UK and the EU have a long track record of jointly tackling global challenges, with strong links already in place between our research and innovation communities. The UK wishes to continue this committed collaboration in areas of shared interest through a partnership with the EU covering research, science and innovation[100].

Research and innovation infrastructures in the UK have a strong and long history of international collaborations, which facilitate transnational access. Our Landscape Analysis indicates that 39% of infrastructure users and 27% of staff come from outside the UK. This is set to continue and intensify. As the landscape becomes increasingly interconnected, there is a **growing need to support and facilitate transnational access to world-class infrastructures.**

10.2 Connecting capability at a national scale

The need to create national-scale capability through **strategic planning of new, distributed infrastructure or better linkage of existing infrastructure** is a common theme across the sectors. These networks or distributed infrastructures can focus around a core technology or methodology (see case study), a research topic or an application. Success requires a proactive community engaged in scoping the precise requirements. This can enable more effective use of resources, provides a more coherent way to develop common skill sets, shares good practice and can foster innovation in methods that inform the planning of subsequent infrastructure.

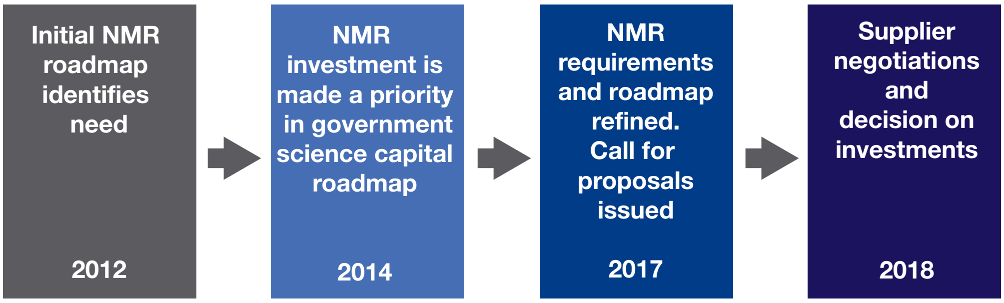
CASE STUDY:
Shaping strategic investment in cutting-edge NMR technology

The development of the first EPSRC Nuclear Magnetic Resonance (NMR) spectroscopy roadmap led to a cross-disciplinary investment of £20 million in ultra-high-field-strength NMR in 2018.

This will create two new systems and a series of upgrades, which are to be linked together as a distributed network across eight universities. This increase in capacity and capability will provide opportunities for research across disciplines.

It was made possible by effective engagement between the Research Councils, the research community and the supplier to deliver improved capacity, capability and value for money through bulk purchase. Work started in 2012 with the development of a community-led roadmap identifying a national requirement.

bruker



For example, the biological sciences, health and food and physical sciences and engineering sectors have both highlighted opportunities to create networks of advanced imaging capability (p28), including mass spectrometry (p55) and a network of instrumentation for sample preparation in techniques such as cryo-EM or MRI (p28-29). Although there is good collaboration across the energy sector, engagement has flagged the potential to also create distributed infrastructure to complement investments to fill gaps in the landscape (Chapter 7, Section 7.2). There is significant potential in the social sciences, arts and humanities sector to improve the connectivity of data, resources and collections, and there is the potential for integrated networks of data repositories across a number of critical themes, for example for storage and access to digital data (p75).

These networks also enable more effective connections to the large-scale facilities, such as Diamond, through 'feeder' instrumentation (Chapter 9). This optimises experimental procedures and sample preparation, making the best use of time available on the most expensive infrastructures.

CASE STUDY:
The UK7T Network: developing an ultra-high-field MRI platform for biomedical research

Ultra-high-field MRI can scan human tissues with greater clarity than ever before, supporting the development of morphological diagnostics for key medical conditions including dementia, cerebrovascular disease and mental health. The UK7T Network, led by the University of Nottingham, links five ultra-high-field MRI centres across the UK (Cambridge, Cardiff, Glasgow, Nottingham and Oxford)[101]. By using harmonised approaches, such as aligning protocols for data-sharing, the network can effectively operate as one large facility, allowing it to undertake large-scale clinical studies across the UK.

The UK7T Network is currently undertaking a large-scale, multi-site study to create a data set of high-resolution brain images from 1,000 healthy adults. This will create a well-curated repository of high-definition brain scans with rich annotation and metadata to identify detailed features of disease and aid early diagnostics and monitoring of disease progression. The UK7T Network is also creating links to other UK disease networks, e.g. the Dementias Platform UK, to create a wider platform to share technical and disease-specific expertise and expand capacity for large and multi-site clinical trials.

10.3 Clusters and local economies

The government's Industrial Strategy[10] recognises places as one of the five foundations of productivity, and the importance of research and innovation is clear throughout the Local Industrial Strategies published to date. The UK's distributed network of research and innovation infrastructures can act as a catalyst for the formation and growth of sector-focused connected clusters of research-intensive businesses and organisations, which can drive local, regional and national economic growth. Formation of localised clusters around one or more infrastructures helps maximise the benefits from investment. Clusters represent a distinct, focused, connected critical mass of research and innovation infrastructures, researchers and businesses in close geographical proximity. Clusters enable rapid knowledge exchange, drive innovation, create partnerships and generate both localised and national economic benefits. This agglomeration of organisations throughout a value chain can attract new high-growth business, skilled people and investors to the cluster, fostering further growth, boosting local employment and enabling cross-sector working. A cluster will reach a critical mass once a number of businesses and research organisations have embedded into a region so that it becomes a location of choice for new businesses, who can exploit the networks and connections to rapidly grow and scale their enterprise using an established platform. This community of innovative disruptive companies also acts as an attractor for established businesses and novel research activities as well as inward investment in that sector. Over time, this can create an innovation infrastructure and an ecosystem that is greater than the sum of its parts, with a strong reputation for capability and collective knowledge that can be leveraged to attract further business and inward investment.

Research and innovation campuses can drive the formation of dynamic connected clusters such as those at the Harwell Campus, Daresbury, Culham, Babraham, Norwich, Easter Bush, Rothamsted and Aberystwyth. Built around world-leading research infrastructure and capabilities, the campuses are creating dynamic innovation ecosystems connecting skills, capability, finance and customers to drive the commercialisation of technologies and innovation arising from the research base.

Productive economic clusters can also emerge around a university or group of universities (e.g. high-performance computing at the University of Edinburgh or the University of Cambridge's biosciences cluster), a large company or public sector establishment (e.g. a hospital with unique capability, defence establishment). The Science and Innovation Audits commissioned by BEIS[102] are helping local and regional areas to map their research and innovation strengths and identify areas of potential global competitive advantage.

CASE STUDY: East Bank: a developing creative cluster

East Bank in London is one of the UK's fastest-growing creative communities and one of the most ambitious new culture and education districts in the world. Over 2,500 jobs are expected to be created across the East Bank development, generating an estimated £1.5 billion for the local economy. Situated in some of London's fastest-growing and most diverse boroughs, founding partners include University of Arts London's College of Fashion, a new venue for Sadler's Wells, new BBC studios and UCL EAST, a new campus focused on art, society and technology.

The Victoria and Albert Museum (V&A) East – a new Waterfront Museum and a new Collection and Research Centre – is currently taking shape at East Bank. The Museum will host a pioneering partnership with the Smithsonian Institution, producing innovative exhibitions and a jointly curated programme bridging arts, sciences, design and the humanities, as well as collaborative research. The Collection and Research Centre will be a unique storage facility housing 250,000 objects and over 900 archives spanning the breadth of the V&A collections, from textiles and fashion to furniture, sculpture, theatre and performance. The goal is to revolutionise access to the V&A's unique collections through creative design of the facilities. A public network will enable visitors to go behind the scenes to discover the collections and watch research in progress. The centre aims to serve as an experimental 'lab' enabling innovative research and modes of engagement and sharing the V&A's collections in ways that have not previously been possible.

V&A Museum

The development of a cluster can be catalysed or stimulated, but it is often an organic process that is dependent on a number of factors. Geographical location might be the most important factor – for example a coastal location might be essential – but the history of a locality is also a critical attractor so that new infrastructure or businesses can draw on the historical expertise, knowledge, networks and wider support that is already present in a region. The availability of critical skills (e.g. at the local university, or through the local training landscape) is often cited by business as a key factor in location decisions[103]. Close working between local and national partners to support and broker development of novel partnerships can also enhance cluster formation[104].

UK Research and Innovation and government PSREs support or form innovative clusters across the UK. The UK Research and Innovation Strength in Places Fund[105] supports consortia of research organisations and businesses to foster innovation-led economic growth in the target geographies. A shortlist of twenty-three projects has been announced for wave 1, and following a second assessment stage in late 2019, UK Research and Innovation expects to fund up to eight of these from 2020. The expression of interest call for Wave 2 bids was launched in May 2019 and this model has the potential to support further waves, subject to funding availability. UK Research and Innovation also supports a number of sector-specific programmes such as AHRC's Creative Industries Clusters programme, which aims to increase connectivity between the UK's creative industries and universities through an £80 million investment in eight new creative R&D partnerships.

CASE STUDY: Harwell Space Cluster

The Harwell Space Cluster includes 89 space organisations employing 950 people (adding 150 new jobs last year). The cluster brings together companies developing technology to go into space, those developing applications to solve global challenges and those taking space technology to new market sectors. This includes multinationals such as Airbus and Lockheed Martin, and SMEs such as Oxford Space Systems and Rezatec.

The Space Cluster coalesced around the longstanding space instrumentation activities of STFC-RAL Space. The arrival of the European Space Agency (ESA) in 2009, the launch of the ESA Business Incubation Centre in 2010 and Satellite Applications Catapult in 2013 (building on the International Space Innovation Centre set up in 2011), along with UK Space Agency opening an office, established the Harwell Space Cluster as the gateway to the UK space sector.

Access to facilities such as Diamond; ISIS Neutron and Muon Source: design, test and validation facilities at RAL Space: and the ESA Climate Office: provides additional opportunities for companies establishing a presence at the Harwell Campus. New facilities such as the National Satellite Test Facility at RAL Space and the Satellite Applications Catapult's Disruptive Innovation for Space Centre are being developed in response to demand from organisations that are already part of the cluster and are proving an attractor for inward investment.

Building on this success, additional clusters in HealthTec and EnergyTec have been established at the Harwell Campus by STFC which provide potential customer bases and multidisciplinary collaboration opportunities. Growth has been supported through the establishment of a public-private partnership. This ensures the focus of the Space Campus is as an R&D centre that continues to drive the development of the unique ecosystem.

10.4 Creating connectivity

A range of mechanisms are used to create connectivity at all scales in the landscape, with examples of good practice across the UK and internationally.

Collaborations and partnerships are the bedrock for connecting research and innovation across the academic, business, charities and public sectors. The effectiveness of infrastructures in some sectors often depends on the support and goodwill of businesses, public service organisations and the public. Research located in hospitals, schools, museums, other public services and local communities is vital to addressing many of the challenges described in this report. This may call for different uses of space and staff time and special governance or co-development of plans for service change and evaluation. The current and future commitment of public service organisations to these partnerships is vital for the UK's competitiveness in these areas.

CASE STUDY:
Cell and Gene Therapy Catapult

Cell and gene therapies rely on modifying biological activity to restore or install functionality by introducing healthy cells, modified cells or new genetic material. Recently, some of the biggest strides in the cell and gene therapy industry have been in oncology, where some therapies have already received approval in the USA and Europe. In the past six years the UK has seen a growth from twenty-two to over seventy cell and gene therapy developers and attracted more than £2.5 billion investment in with an increase from twenty-one to over eighty active clinical trials.

The Cell and Gene Therapy Catapult based in London seeks to provide a platform for cell and gene therapy companies to grow and flourish in the UK. The Catapult's manufacturing centre opened in Stevenage in April 2018 backed by over £60 million in investment from the UK government's Industrial Strategy. Its unique collaborative operating model allows companies to develop their manufacturing processes at scale, to Good Manufacturing Practice standards and underpinned by end-to-end expertise and practical support from experts across scientific research, manufacturing, supply and regulation. The modular nature of the facility allows companies to expand and add additional collaborations, for instance viral vector manufacturing as well as cell product manufacture.

There are currently five companies developing their manufacturing processes at the centre. TCR2 was the first US company to have committed, joining Adaptimmune, Autolus (both of which have now reached unicorn status), CellMedica and Freeline. 2019 will see the opening of an additional six clean rooms for manufacturing which will increase the capacity of the centre to support the growth of companies.

Catapult Network

CASE STUDY:
UKRPIF and the High Temperature Research Centre (HTRC)

The UK Research Partnership Investment Fund (UKRPIF) encourages strategic partnerships between HEIs and other organisations. Since its establishment in 2012 it has provided over £900 million to fifty-four research projects attracting £2.2 billion in double-match funding from non-public sources[106]. The HTRC is a unique world-class casting, design, simulation and manufacturing research facility established by the University of Birmingham in partnership with Rolls-Royce. The centre was established with £20 million in funding from the UKRPIF and £40.3 million from Rolls-Royce. It focuses on underpinning materials research, radical process improvements and predictive processing modelling.

The key to raising the TRL at which research works has been equipping the centre to the level of a Rolls-Royce plant, with considerable input from Rolls-Royce. Research can quickly be tested in manufacturing processes without disrupting the highly automated production processes of an operational plant.

The centre can demonstrate new manufacturing capabilities that significantly reduce the time to design and manufacture components for engine development programmes. For example, the first HTRC programme achieved 13 months from start of design to delivery of test hardware. It has also allowed new training opportunities, with apprentices, Rolls-Royce staff and researchers co-located and working together within a facility that can operate at significant scale.

Equipment-sharing initiatives support investment in higher-specification capability, enabling a wider range of research and creating management efficiencies. Clusters of research-intensive universities have implemented instances of more formal asset- sharing, e.g. the N8 or Midlands Innovation. Networks of cutting-edge precision equipment, such as those established through the Clinical Research Capabilities and Technology Initiative[107], are designed to be in close proximity to clinical investigation and care facilities in order to effectively advance clinical research. However, barriers to tax-efficient sharing of facilities remain[108].

Funding community networks has successfully catalysed integration of distributed capability. In the UK, BioimagingUK[109] – a multi-funder network (BBSRC, EPSRC, MRC, the Wellcome Trust) – together with facility managers meetings and learned societies, has led to the sharing of good practice within the bioimaging research community. This includes training guides, technical expertise and the establishment of a central database of microscopy facilities, hosted by the Royal Microscopical Society. The League of European Accelerator-based Photon Sources (LEAPS) network fosters close collaboration between European Light Sources such as the UK-based

CASE STUDY: Bridging for Innovators (B4I)

STFC's B4I programme is piloting a new approach to helping businesses, particularly SMEs, tackle their productivity challenges through access to STFC's high-tech scientific facilities. Starting in late 2017 the programme has received eighty-nine business applications and has been supporting twenty-seven business users including £614,000 in industrial match-funding, as of June 2019[111].

Cobham RAD Europe Ltd used ISIS Neutron and Muon Source's ChipIr beamline to bring a new product – the Aviator S – to market. This device is intended primarily for communicating flight data between the aircraft and the ground but has a potential secondary role through its Passenger Information and Entertainment Services (PIES).

With this device, airline passengers would be able to stay in touch with social media and emails without interrupting the aircraft's operations. Even though this device is not safety-critical to the aircraft's operation, it still needs to pass vigorous testing before it can be used commercially. One of these tests is the resilience of the device to neutrons generated by cosmic rays.

The ChipIr beamline at ISIS Neutron and Muon Source can test the effect of many years of exposure to cosmic neutrons in just one day. By using ChipIr, Cobham were able to identify any issues caused by the radiation and ensure changes were made so the equipment met the standards required. "Having access to a world-class neutron facility like ISIS here in the UK is a huge advantage for Cobham," says Dr Richard Sharp, the company's Managing Director. "The alternatives are located in North America, so there is a significant cost advantage in using ISIS for the testing and qualification of our aerospace equipment."

Hiljon from Pixabay

Diamond. The LEAPS Strategy 2030 seeks to deliver better collective capability through smart specialisation, closer cooperation, better engagement with industry and collective outreach to new users[110].

Broadening access to our infrastructure requires a combination of awareness-raising and active facilitation and support. This programme has focused on infrastructures that offer access beyond their individual institutions, and stakeholders have emphasised the need to remove barriers and open up or facilitate access. Access models depend on the type of infrastructure and may involve peer review of proposals, be dependent on specific permissions (e.g. medical infrastructures) and in some cases require transfer or digitisation of materials and resources (e.g. museum collections). Broadening access requires staff who have the right skills to engage and partner with new users, trade bodies and businesses, helping them understand the infrastructure capability and potential benefits. The Horizon 2020 Transnational Access scheme has been successful in opening up key national and regional research and innovation infrastructures to European researchers from academia and industry.

Increasing awareness and discoverability: Many consultees over the course of the programme commented on how difficult it can be to know what infrastructure the UK has to offer. This acts as a barrier to broadening use and building connections. Tools can help new users find out what capability might be available. The equipment-sharing portal Equipment.data[112] supports the search for equipment at a wide variety of UK universities and the number of contributors continues to grow. The National Centre for Universities and Business has developed an online brokering tool, Konfer[113], to help businesses find the relevant expertise and assets they need from within universities. UK Research and Innovation will also share the data gathered on existing UK infrastructures through a portal alongside this report.

Public participation in trustworthy research programmes and infrastructures is also essential. At any one time, several million UK citizens are participating in research studies, especially in the social, environmental and health research sectors. Our research capabilities in these areas need to reflect the diversity and rate of change in our population, make use of new technologies to facilitate richer data capture, facilitate fuller participation of volunteers and ensure appropriate governance and privacy safeguards. As we plan towards the future, public engagement and participation will remain a key factor in supporting and embedding the research and innovation culture in the landscape and beyond; reaching out to new communities and sectors will enrich the landscape through these new forms of connectivity.

10.5 Integrating innovation

Many of the challenges and themes outlined in this report require the testing of ideas at scale to show how technologies or data might integrate or how potential solutions might operate in the real world. There are several types of infrastructure that can help achieve this, including demonstrators, test beds and living labs, which support greater integration of academic, business, charitable or public sector research and provide routes to follow on funding and private sector investment[114].

Key objectives are to de-risk the development, scale-up new solutions and services and expose and address barriers to implementation. This can give potential users or markets (both public and private) the confidence to invest. **Given the proximity to market, scale and complexity of such infrastructures, partnership-working is often a key feature to bring together all the elements needed for success**.

Demonstrators are near-market projects testing solutions in real-life conditions and taking a whole-systems (cross-sectoral) approach to de-risking or scaling-up implementation. Given the cost and proximity to market, they are often collaborations between public and private sectors. Existing examples include:

- The SPECIFIC Innovation and Knowledge Centre
- ISCF-funded local energy system demonstrators
- ISCF-funded robotics and AI demonstrators

Test beds are specifically set up to enable companies to plug into infrastructure that they otherwise would not get access to or could not afford. They bring together business, academia and the public sector to work with users in co-designing, testing and implementing new services. Existing examples include:

- 5G test beds
- The Digital Catapult's Things Connected Network
- The Propulsions Future Beacon test bed

Living labs are user-centred and often based in a particular geographical location, e.g. a city, region or landscape. They integrate concurrent research and innovation processes within a citizen-public-private partnership and may be critically dependent on the commitment and capacity of organisations such as hospitals, schools or local authorities. Existing examples include:

- The Energy Systems Catapult Living Lab
- North Wyke Farm Platform
- The UKCRIC Bristol Infrastructure Collaboratory

CASE STUDY: Offshore Renewable Energy Catapult

Subsea surveys and inspections are a necessary part of maintaining an offshore wind farm, but current methods are laboriously time-consuming and expensive. Bristol-based SME Rovco deliver cutting-edge subsea survey services. Their pioneering underwater live 3D-vision SubSLAM technology provides offshore wind owner/operators with a clearer and immediate picture of their subsea assets, with the potential to lower the cost and improve the quality of subsea inspections by 80%.

Rovco secured grants from Innovate UK and private investment to develop the 3D-vision camera system along with AI integration, conducting system testing and validation at the Offshore Renewable Energy Catapult in Blyth. The Catapult's unique dry-dock testing facility features a replica seabed, allowing technology developers to carry out trials in a controlled subsea environment, whilst experienced offshore personnel and R&D technicians have the capabilities to replicate the conditions found on an operational offshore wind farm site, boosting bankability and investor confidence in innovative solutions that perform well.

Rovco has since secured significant backing from Global Marine Group (GMG) and both companies will work together to deliver a range of efficient, high-quality subsea solutions to improve data acquisition. Rovco's SubSLAM technology will be deployed from GMG's fleet of twenty-one specialised crew transfer vessels. With an estimated export revenue of £20 million per year, Rovco's subsea robotics expertise has put the firm in line to become the market leader in subsea surveying.

ORE Catapult

This extends beyond funding partnerships to in-kind contributions such as the sharing or use of assets (e.g. land, equipment, data) between academic researchers, businesses, national and local government, public service providers and the general public. Bespoke arrangements are often needed to ensure appropriate governance and to take account of any regulatory, legal or standards constraints[115]. UK Research and Innovation and many PSREs already fund activity in this space. Over the longer term our ambition is to develop more capability in this area; for example, the biological sciences, health and food sector chapter highlights opportunities for accelerators and small-scale manufacturing, quality control and trial facilities bringing academia, industry and the NHS together. The physical sciences and engineering chapter discusses the need for higher-TRL test beds and demonstrators to develop future transport solutions (p61) and the opportunity for living labs or demonstrators to explore the intersection of autonomous vehicles, smart infrastructure, robotics and smart services (p62). The social sciences, arts and humanities sector chapter discusses opportunities for integrated environments which combine digital connectivity with physical spaces, embracing new technologies to open up new ways to create products and experiences (p66). The Environment sector's requirements include demonstrator or test bed facilities in geothermal energy and heat storage, CO_2 storage and integrated networks of sensors forming 'landscape laboratories' to gather data on our environment (p93). Given the proximity to market, the energy sector identified multiple opportunities for demonstration and test bed activities across the different energy technologies (Chapter 7).

There is also scope to further explore good practice in establishing such activity and how best to take forward some of the ideas set out in this report, many of which are outside the remit of any single funding organisation. One such activity is that the Royal Academy of Engineering, as part of the National Engineering Policy Centre, is aiming to develop best practice in establishing and operating demonstrators through engagement with stakeholders, including businesses. The ISCF also provides a mechanism to foster the development of demonstrators, test beds and living labs, as well as considering other infrastructure needs to support a challenge, for example characterisation infrastructure for the Battery Challenge[116].

Important infrastructure may also be located in the private or charitable sectors. A recent mapping of industrial digitalisation technologies by Innovate UK and the Knowledge Transfer Network captured both public and private facilities with open access[117]. This offers a potential approach to capturing a fuller picture of UK infrastructure that may be accessible to users outside of individual companies.

CASE STUDY: North Wyke Farm Platform: a 'living lab'

The North Wyke Farm Platform is a unique research facility or 'living lab' for the study of sustainable livestock farming on grassland, particularly beef cattle and sheep production. Managed by Rothamsted Research and based near Okehampton in Devon, the facility provides access to a range of state-of-the-art instrumentation in hydrologically isolated catchments and fields alongside remote access to the data generated by the facility. This supports research into replacement of nitrogen fertilisers to reduce energy consumption and greenhouse gas emissions, use of plants to manage soils and provide green-engineered solutions to flooding, efficient use of water resources and animal health. For example, the unique design of this platform enabled researchers to link soil health, pasture value and sustainable livestock production, suggesting that managing soil by well-designed grazing (e.g. by changing rotational grazing patterns) could improve livestock productivity.

Rothamsted Research

Chapter 11: Critical enablers and policy issues

Previous chapters have highlighted opportunities for new capability across the landscape, but the full benefits of both new and existing infrastructures will not be realised without addressing critical enablers and challenges. Considerations around skills, data and sustainability were the top barriers to effective operation of infrastructures identified in our Landscape Analysis questionnaires. They are important for infrastructures at all scales and in all sectors. The underpinning policies and approach to the issues will have major impact on how our infrastructures are set up, their scope, their ability to operate and their future sustainability.

11.1 Skills and training

The availability of specialised skilled staff is critical to the operation of infrastructures across all sectors. This workforce is diverse, including research technicians, technology skills specialists, infrastructure managers and other professional groups. They represent a significant proportion of the UK's overall R&D workforce: 31% of the business and 10% of the higher education workforce in 2015[118] and 36% of the staff in the infrastructures covered by our Landscape Analysis. Public sector research and innovation organisations act as both employers and a training ground for professional skills in the wider economy. UK Research and Innovation is a direct employer of over 2000 research technology professionals within its research and innovation facilities, institutes, centres and campuses. As well as developing and operating the infrastructure itself, these professionals perform other vital roles such as data analysis, training others in the use of infrastructures, working alongside visiting research teams on particular projects and developing new and transformative technologies and methodologies.

The **challenges around skills recruitment and retention were considered the top barriers to effective operation by infrastructures** responding to our questionnaires, with resulting impacts on their ability to act at capacity. This problem is growing as the workforce ages and demand increases. In England, 40% of the higher education technician workforce is aged 50 or over, highlighting the challenge of succession planning[119]. Estimates from the Gatsby Foundation indicate that the UK will need 700,000 new technicians by 2020 to meet the demand from employers[120]. Public sector organisations struggle to provide salaries on a competitive level with the private sector, universities and the international market. Across the landscape, demand already exceeds supply in a number of areas that have been highlighted through the roadmap programme in relation to **digital and analytical skills, data science and AI, software engineering** and the interface with other disciplines. The demand for such skills will only become more acute in response to the infrastructure requirements described throughout this report. Already one in ten UK job adverts are for professional data experts according to a labour market analysis commissioned by the Royal Society[11]. Demand has grown across all levels of data expertise but especially for advanced roles. One in two job adverts for data scientists require machine learning (up 3,214% since 2013) and one in eight demand AI (up 7,664% since 2013).

The talent market is global and the UK is reliant on the ability to attract overseas skilled technical and specialist people at all stages of their career. 39% of the staff employed at the infrastructures in our Landscape Analysis are from overseas. Nearly 90% of EU and non-EU technicians at Russell Group universities are skilled to National Qualification Framework level 6 and above and 25% hold a PhD[121], yet they do not hold a clear professional status under the current Standard Occupational Classifications for recognition in the Tier 2 visa system. This risks creation of additional barriers to recruitment and retention of the expanding technical workforce.

A long-term perspective and career track are key to increasing the attractiveness of infrastructures as employers[122] and supporting the international mobility of specialist staff. At the institutional and national level, clarity of the career path for such professionals is often lacking. Stakeholders have told us the visibility of these professions is often low and roles 'underappreciated', whether that be directly through lack of recognition of contributions to academic papers and grant proposals, or indirectly in terms of their overall contribution to the management of facilities and training of users[123,124]. Further work is needed to **develop a clear identity for different professional groups.** This includes clarifying **career structures, options, incentives and training needs** for these

CASE STUDY:
Developing technical career roles and pathways: examples across the sectors

The **National Technician Development Centre** provides organisations and technical communities with information, expertise and tools. This includes the Technical Development and Modernisation toolkit developed as part of a project with eighteen HEIs to identify the major challenges facing technical staff and services. The toolkit provides guidance on career pathways and staff development to support organisations in meeting pledges made as part of the Science Council's Technician Commitment.

EPSRC supported the research software development community to self-identify as research software engineers through the **Research Software Engineering Network and Fellowships.** This raised awareness of the importance of software development, brought the community together and aided development and retention of staff.

To address the shortage of appropriately trained technicians in synthetic biology, the **UK Centre for Mammalian Synthetic Biology**, based at the University of Edinburgh, is hiring school leavers as **modern apprentices** in its specialist research facilities. The apprentices work in the laboratories while gaining formal qualifications as lab technicians. After completing his training, the Centre's first apprentice, Scott Neilson, began work at the Edinburgh Genome Foundry, one of the largest automated genome assembly platforms in the UK. There he has become indispensable operating and maintaining the highly sophisticated platform for DNA assembly and proving an adept instructor of foundry customers. Scott is currently working towards an Higher National Diploma and potentially, in the future, a part-time degree.

Michal Jarmoluk from Pixabay

professions, building on examples of good practice. Many organisations have a role to play in taking this forward and work is already under way through, for example, the Technician Commitment initiative led by the Science Council and Gatsby Foundation[125], through the Technical Development and Modernisation project[126] and through Higher Education and Technician's Educational Development (HEaTED)[127]. Successful examples are often led by the professions themselves but this needs to be catalysed and supported.

The Industrial Strategy includes an aspiration to develop the UK's technical skills base including specific skills identified in the Grand Challenge areas. The creation of UK Research and Innovation provides opportunities to work closely with other stakeholders and demonstrate leadership by **supporting the development of the professionals we employ directly and those employed through our work to fund the wider landscape.**

In developing its Talent and Skills Strategy, UK Research and Innovation is taking an overarching view on what a healthy and thriving future research and innovation workforce will look like and the interventions required to support it. The UK Research and Innovation Statement of Expectations for technology/skills specialists[128] sets out the expectations of research organisations, UK Research and Innovation and individual technical staff to ensure parity of esteem between technical and academic staff and access to improved career development and progression opportunities. Alongside this, UK Research and Innovation's intention is to engage with the Technician Commitment initiative to ensure visibility, recognition, career development and sustainability for those professionals directly employed by the organisation[129]. Subject to resource availability, there is also the potential for UK Research and Innovation's existing infrastructure to act as centres of excellence for training of the next-generation of technical specialists to address skills gaps, both for our own workforce and the wider economy.

11.2 Data management and access

A critical thread running through all chapters in this report is the **rising opportunity for connected, large-scale data** that can be readily analysed to generate insights and innovation. This explosion in 'big data' comes as the use of numerical and predictive simulations rises to increase accuracy or to interpret data over longer timescales or across greater scales. Advanced statistical techniques such as machine learning can be transformative but larger data sets will require advanced computing facilities and new skill sets as discussed in Chapter 8.

The **data landscape is complex and multi-layered**. Researchers and innovators require: infrastructures that can share data in accessible formats; data environments where large and complex data can be analysed, integrated, visualised and managed; and databases that allow the ready upload or download of data. All sector chapters in this report include opportunities for infrastructure capability that will generate new data and support analysis, building on our existing data infrastructure.

The diversity of data sets (historical and new, created for research purposes or from non-research sources) brings new challenges with the potential to unlock value through data linkage. Chapter 8 set out the need for **more detailed analysis of research data infrastructure requirements**, including opportunities for sharing or co-locating data infrastructure and services.

Any analysis of infrastructure requirements needs to go hand in hand with developments in data policy. Data access should be as open as possible and as closed as necessary, and fully consider personal, commercial and security issues. The **development of Open Science and Open Data** policies has meant that there are greater efforts to make research, government and private sector data open and available for use. This desire for openness, coupled with advances in data analytics and associated technologies, is a key driver of innovative practice and new infrastructure opportunities. The Open Data Institute recently launched the findings of its data trust programme, finding huge demand for legal structures that provide independent stewardship of data[130].

CASE STUDY:
Archaeology Data Service (ADS) as a world-leading data repository

The Archaeology Data Service (ADS) is a world-leading digital heritage data archive that has been leading the development of digital preservation since 1996[134]. It engages with the preservation community about developments in data policy and good practice in data repository creation and management.

Prof Amanda Claridge, Prof Helen Rendell

Photograph of a brick found during one of the excavations. It bears a stamp with Caesar Augustus' name dating it to between 27 BC and 14 AD.

The ADS is the deputy lead of the Advanced Research Infrastructure for Archaeological Dataset Networking in Europe. This international research infrastructure fosters collaboration, data interoperability and infrastructure connectivity. In 2019 it established Saving European Archaeology from a Digital Dark Age, a new four-year action with thirty Partner Countries. The ADS is also driving the development of data policy for the European Research Infrastructure for Heritage Science (E-RIHS), part of an emerging global distributed research infrastructure. Through these international research collaborations, the ADS is pioneering new ways of managing and curating complex data and developing a shared evidence base for interdisciplinary research to ensure the integrity, reliability and accessibility of complex data.

In 2012 the ADS was awarded the Digital Preservation Coalition's Decennial Award for the most outstanding contribution to digital preservation of the decade.

Open Data policies are being developed across funders to support the development of a culture where sharing data is part of the research process. The development of the concept of FAIR data[131] has transformed expectations around both sharing and the management of data, and the concept is being extended further (for example, into software). UK Research and Innovation has developed common principles on data policy[132] and the Open Research Data Concordat working with other stakeholders, e.g. Universities UK[133]. UK Research and Innovation Councils have comprehensive Open Data policies and support the use of data management plans. Work is currently ongoing to harmonise the Data-Sharing Policies and review UK Research and Innovation's policy on open access to publication outputs. Research Data Management and Open Data policies need to be developed in partnership with data infrastructure providers and users. **A more detailed assessment of the requirements for implementing the FAIR principles within each sector is needed.**

UK Research and Innovation will continue to work with other external organisations, particularly those that also support infrastructure (such as the Wellcome Trust and Jisc), to develop its Open Research Data Strategy. **UK Research and Innovation will also consider developing a strategy for Data Access,** building on this existing work and considering opportunities for sharing and co-locating infrastructures and services, alongside engaging in the work of the G7 around a global agenda on an Open Science Cloud.

11.3 Sustainability of infrastructures

Research and innovation infrastructures are long-term investments. Infrastructures need to be sustainable not just in terms of funding but also organisationally, technically and in terms of their human resources. They also need to be responsive to changes in user needs and disruption from new technologies, evolving and developing their approach over the course of their lifecycle. In some cases infrastructures have a finite lifetime before user needs and

CASE STUDY: Evolving the infrastructure landscape: accelerator science

The Accelerator Science and Technology Centre (ASTeC) was created in 2001 as a centre of excellence for study of the production, acceleration and delivery of charged particle beams.

Originally based at the Daresbury Laboratory, it was born from decades of advanced particle accelerator research and development at the Synchrotron Radiation Source (SRS) facility, which was closed in 2008 after twenty-eight years of operation and 2 million hours of science[135].

ASTeC now carries out programmes of research and design in support of STFC's large-scale multidisciplinary facilities, drawing on the extensive experience of accelerator science and technology staff originally employed at the SRS. SRS and ASTeC users and staff also had a significant impact on the establishment of Diamond. Many worked on the early conception and design as well as using skills and experience from the SRS to model and re-engineer the beamline components[136].

technology development requires something different. In other cases the value and potential of an infrastructure increases over time, e.g. longitudinal data sets or physical collections.

Although the duration and planning cycle of an infrastructure will vary substantially according to the nature of its work, they are typically operational for many years and in development for some time before that. **Stable support and a long-term investment plan** are vital to enable the full benefits to be realised for users, potential co-funders and the wider economy. Many infrastructures operate in complex funding landscapes, drawing on multiple streams of varying duration over the course of their lifecycle. When the initial capital funding to set up an infrastructure is provided, the source of the ongoing operational funds, including staffing costs, may need to be drawn from elsewhere.

Funding for the early-stage investigation of new infrastructures, such as scoping activity, conceptual design and feasibility studies, is not always available. Our consultations over the course of the roadmap programme and the Landscape Analysis illustrated the challenges faced by infrastructures due to the difference in their expected duration and the frequency of funding decision points. 60% of infrastructures in our analysis have an expected operational lifetime of over twenty-five years but only 41% felt able to plan one to three years ahead[18]. Many infrastructures also have high fixed-to-marginal-cost ratios, which mean small budgetary changes have an amplified impact. Although predictable funding cannot be guaranteed for the full lifecycle, this can make it challenging to ensure infrastructures are operating optimally and supporting long-term operations and ongoing technology development.

CASE STUDY:
Investing to save: the RRS Sir David Attenborough

Research in the Polar Regions is fundamental to understanding the impact of polar ice melt and its effect on climate change. NERC's two existing ice-strengthened ships, the RRS *James Clark Ross* and the RRS *Ernest Shackleton*, provide a vital platform for leading edge multi-discipline science. However, at the time the business case was put together, the current operating costs of £50 million a year were expected to increase over the next five years, particularly if both ships were extended past the end of their planned lives in 2019.

To deliver better value for money, NERC is investing £966 million over thirty years for a single polar research vessel, the RRS *Sir David Attenborough*. Replacing existing polar ships with a state-of-the-art new vessel will reduce fuel, staffing and maintenance, cutting operating costs by 20%. As well as providing an advanced research capability, this timely investment is estimated to save £102 million and lead to the generation of £2 billion of wider economic benefit to the UK through securing UK international leadership in polar science.

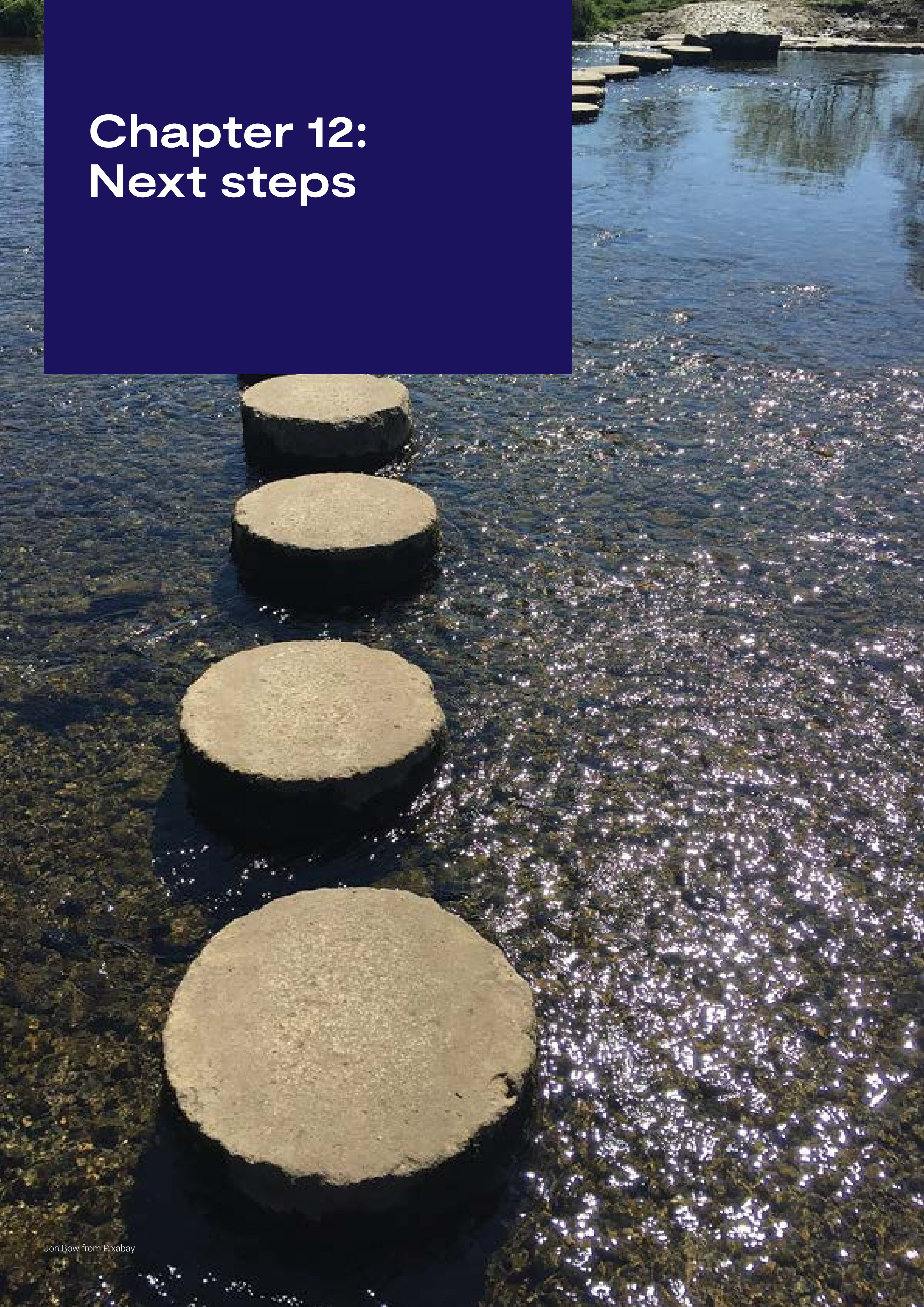
Rolls-Royce

There are also tensions between the establishment of new capability against maintaining and developing existing infrastructures and meeting any costs associated with decommissioning. The UK has invested in significant new infrastructures in recent years alongside many well-established capabilities. This is an important part of the pathway to increase total R&D investment to 2.4% of GDP. All of these infrastructures have long-term operational requirements, although no infrastructure can expect to be funded indefinitely. Ensuring efficient operation and adopting new technologies, e.g. automation, can help manage financial pressures but require investment in change to realise benefits later down the line. Tensioning these choices is a critical part of managing any infrastructure portfolio with a finite budget within individual institutions, funding organisations or more broadly across the UK. UK Research and Innovation is **establishing a clear approach to managing its infrastructure portfolio** which will take account of issues of sustainability and continue to ensure value for public investment. This will draw on this report to inform the decision-making process.

This process for deciding on infrastructure investments needs to be underpinned by a clear cycle of monitoring, review and performance evaluation. This helps us understand scientific and wider impacts ensure quality and value for money, and supports learning to inform future approaches[137].

Given the diversity of the landscape, there is no single approach to monitoring or evaluation a research and innovation infrastructure. Any monitoring and evaluating processes need to be fit for purpose, planned early in the lifecycle and scoped to support the particular decisions to be made. Examples of good practice have been highlighted by the European Commission[138,139], including guidance on useful metrics and measures. UK Research and Innovation impact evaluations are undertaken in line with the principles set out in the government's overarching appraisal, evaluation and quality-assurance frameworks[140,141,142,143]. Where necessary, UK Research and Innovation evaluations also consult more detailed research and innovation evaluation guidance using the BEIS Science Capital Appraisal Framework[144].

Chapter 12: Next steps



Jon Bow from Pixabay

This report provides an assessment of the future UK research and innovation infrastructure landscape. It summarises significant work and community engagement over the last eighteen months and builds on the Progress Report, reflecting the feedback received and further work to develop options for delivering the capability needs identified and ways forward on cross-cutting issues.

This report is intended as a **strategic guide to inform future investment decisions and identification of priorities** for the next-generation of infrastructure to 2030. In the context of the goal to reach 2.4% of UK GDP invested in R&D by 2027, the report is deliberately ambitious and provides an overview of potential infrastructure opportunities that could lead to a step-change in the capability available to researchers and innovators over the next ten years.

Although this report already focused on areas which could lead to a step-change, we have not attempted to prioritise across the capabilities set out in this report. Ultimately, future funding to develop existing infrastructures or create new capability set out here will be dependent on strategic investment decisions and availability of funding from a range of organisations including the government and UK Research and Innovation. UK Research and Innovation is establishing **a clear approach to managing its infrastructure portfolio** to address issues of sustainability and continue to ensure value for public investment. We will use this report to inform the prioritisation of infrastructure investments alongside additional work to explore costs and feasibility of projects (Figure 21). The details will be subject to the outcome of future spending decisions in which BEIS will be making the case to HM Treasury for funding for research and innovation, taking advice from UK Research and Innovation and other delivery partners including the academies and PSREs. The principles below, which draw on international good practice[145,146], will be important:

- A continued focus on **excellence with impact** alongside consideration of the **strategic drivers, value for money and deliverability** of any investments
- The appropriate **independent advice and input** as a vital input to decision-making
- Decisions to fund new infrastructures **taking into account the full lifecycle costs** including future operation, staffing and any future decommissioning costs whether there is enough demand, strong governance and incentives to ensure efficient and effective use
- **Maintaining flexibility** to respond to emerging priorities and new financial pressures
- Supporting the **early-stage scoping and R&D** which may lead to development of new infrastructure capability as part of a developing portfolio
- Considering the potential for **international collaboration and partnership**

In its Strategic Prospectus, UK Research and Innovation committed to ensuring **energy efficiency and environmental sustainability** in everything we do. These are also critical factors to consider in future decision-making around infrastructure development where, for example, infrastructures require significant power supplies or have the potential to showcase new technologies and practices.

Individual Councils within UK Research and Innovation have delegated responsibility to manage the infrastructure portfolio within their domains taking advice from their Councils, but many investments are of a cost that cannot be accommodated within these budgets, cut across multiple domains or are of a scale that requires approval from government. BEIS Ministers will guide the strategic direction of this process, agreeing major strategic priorities, approving spending decisions on major capital projects and steering the balance of funding between UK Research and Innovation Councils. The above principles are relevant in all cases.

Our intention is to build a pipeline of ideas and infrastructure requirements for the longer term, and ensure the underpinning role of e-infrastructure is reflected in funding structures and decisions. As set out in Chapter 2 we have captured ideas at different stages of development, from those which require further scoping to those where the requirement and implementation plan are clearer. **Further work to define and scope ideas which are at earlier stages of development** will follow in anticipation that they can feed into the portfolio over time.

This report is a 'living document' which can be updated as new ideas arise and others become a lower priority. We will **keep the report under review with a regular, more substantial refresh every few years** in consultation with the research and innovation community.

As this is the first exercise of this scale undertaken in the UK, there are many lessons learned we can build into future iterations. For example, future editions could include greater consideration of the infrastructure landscape outside of the public sector, explore opportunities to create links across the landscape in more depth and forge stronger links across sectors particularly in the area of data science.

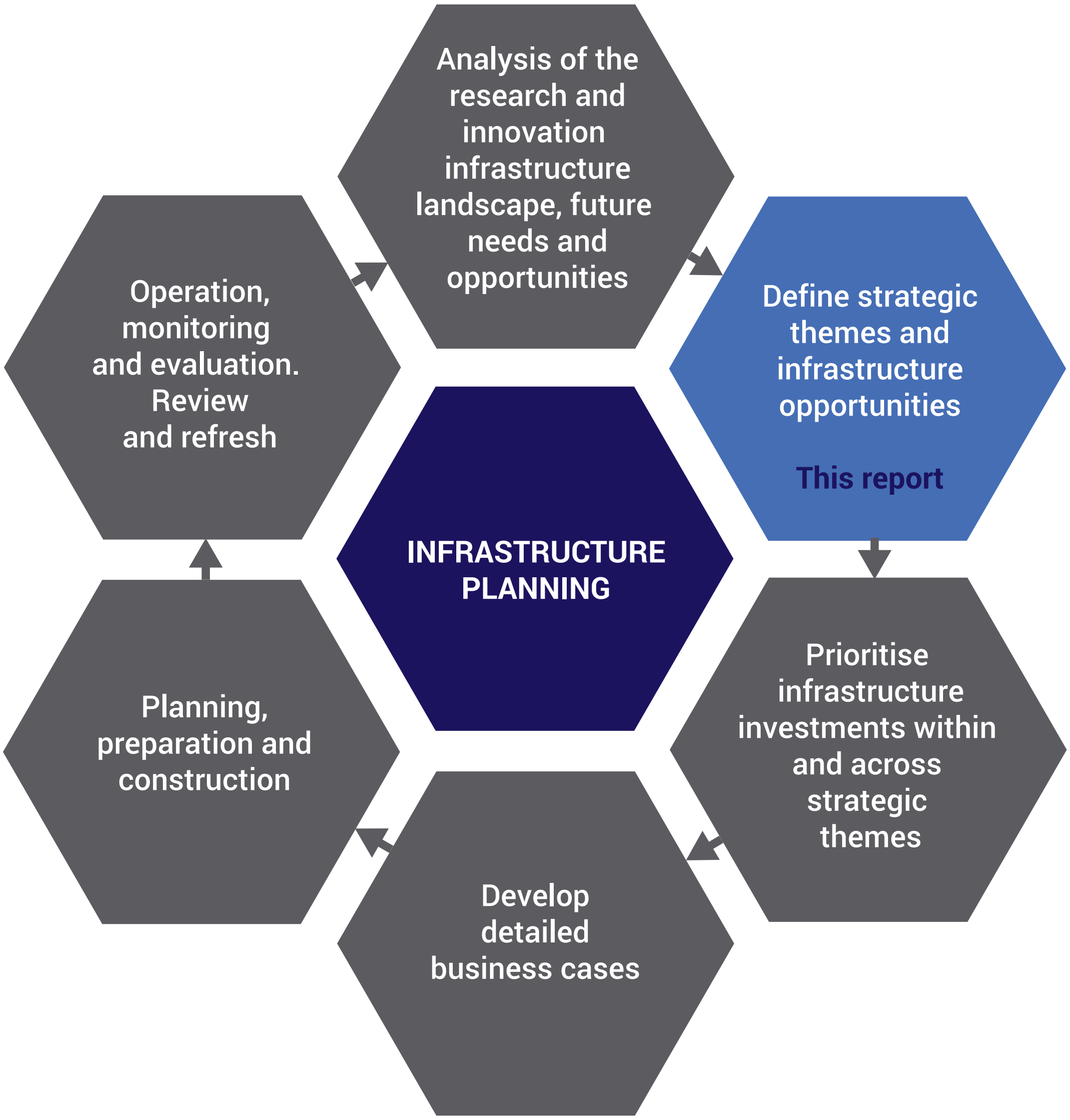


Figure 21. Overview of infrastructure planning process.

Acknowledgements

This report has been prepared by UK Research and Innovation with support and advice from the following organisations: Met Office, National Physical Laboratory (NPL), UK Atomic Energy Authority (UKAEA), UK Space Agency (UKSA), National Nuclear Laboratory (NNL), Department for Business, Energy and Industrial Strategy (BEIS), Higher Education Funding Council for Wales (HEFCW), Scottish Funding Council (SFC), Department for the Economy of Northern Ireland (DfE NI), Royal Society, Universities UK and Association for Innovation, Research and Technology Organisations (AIRTO).

We are very grateful for the significant engagement of over 900 infrastructures, universities and other organisations who responded to the landscape questionnaires and the many stakeholders who participated in one or more of the dedicated workshops and meetings or provided advice through UK Research and Innovation's advisory networks, including its Councils and strategic boards and committees. We are also grateful for insights from colleagues responsible for the development of roadmaps in other countries and from European Strategy Forum on Research Infrastructures (ESFRI) and to international representatives who participated in a workshop at the 2019 Annual Meeting of the American Association for the Advancement of Science (AAAS).

Acronyms and abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
AAAI	Authentication, Authorisation and Accounting Infrastructure
AAAS	American Association for the Advancement of Science
ADR UK	Administrative Data Research UK (previously ADRP)
ADS	Archaeological Data Service
Agri-EPI	Agricultural Engineering, Precision and Innovation Centre
AHRC	Arts and Humanities Research Council
AI	Artificial Intelligence
AIRTO	Association of Innovation, Research and Technology Organisations
ALICE	Accelerators and Lasers In Combined Experiments
ALICE -	A Large Ion Collider Experiment
AMR	Advanced modular reactor
AMR	Antimicrobial Resistance
ARTFUL	Advanced infrared/Terahertz Facilities for Users of Lasers
ASTeC	Accelerator Science and Technology Centre
ATLAS	A Toroidal LHC Apparatus
AWE	Atomic Weapons Establishment
BBC	British Broadcasting Corporation
BBSRC	Biotechnology and Biological Sciences Research Council
BEIS	Department for Business, Energy and Industrial Strategy
BSL-3	Biosafety Level 3
CAT3	Category 3
CCS	Carbon Capture and Storage
CERN	Conseil Européen pour la Recherché Nucléaire (European Organisation for Nuclear Research)
CHAP	Crop Health and Protection
CHP	Combined heat and power
CLF	Central Laser Facility
CMS	Compact Muon Solenoid
CO_2	Carbon Dioxide
Cryo-EM	Cryo-Electron Microscopy
CT	Computed Tomography
CUBRIC	Cardiff University Brain Research Imaging Centre
DAFNI	Data and Analytics Facility for National Infrastructure
DCMS	Department of Culture, Media and Sport
Defra	Department for Environment Food and Rural Affairs
Diamond	Diamond Light Source
DiPOLE	Diode Pumped Optical Laser for Experiments
DiRAC	Distributed Research utilising Advanced Computing
DSTL	Defence Science and Technology Laboratory
EBI	European Bioinformatics Institute
ELI	Extreme Light Infrastructure
ELIXIR	European Life Science Infrastructure for Biological Information
EMBL	European Molecular Biology Laboratory
EMBL-EBI	European Molecular Biology Laboratory - European Bioinformatics Institute
EMEC	European Marine Energy Centre
EMPHASIS	European Infrastructure for Multi-scale Plant Phenomics and Simulation
EPAC	Extreme Photonics Application Centre
EPSRC	Engineering and Physical Sciences Research Council
E-RIHS	European Research Infrastructure for Heritage Science
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESRC	Economic and Social Research Council
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EU	European Union
Euro-Bioimaging	European Research Infrastructure for Imaging Technologies in Biological and Biomedical Sciences
EuroMod	Tax-benefit microsimulation model for the European Union
European XFEL	European X-ray Free-Electron Laser Facility
FAAM	Facility for Airborne Atmospheric Measurements
FAANG	Functional Annotation of Animal Genomes
FAIR	Findable, Accessible, Interoperable, Reusable
FEL	Free Electron Laser
FELIX	Free Electron Lasers for Infrared eXperiments
G7	Group of Seven (Canada, France, Germany, Italy, Japan, the UK and the USA)
GDP	Gross Domestic Product
GLAM	Galleries, Libraries, Archives and Museums
GVA	Gross Value Added
GW	Gravitational Wave
HDR-UK	Health Data Research-UK
HEaTED	Higher Education and Technician's Educational Development
HEI	Higher Education Institution
HE-LHC	Higher-Energy Large Hadron Collider
HiLUX	Ultrafast Structure and Dynamics at RCaH
HIV	Human Immunodeficiency Virus

HL-LHC	High-Luminosity Large Hadron Collider
HPC	High-Performance Computing
HTC	High-Throughput Computing
IBD	Inflammatory Bowel Disease
ICR	Institute of Cancer Research
ICT	Information and Communications Technology
IIIF	International Image Interoperability Framework
ILL	Institute Laue-Langevin
Instruct-ERIC	Integrated Structural Biology – European Research Infrastructure Consortium
InTEGReL	Integrated Transport Electricity Gas Research Laboratory
ISCF	Industrial Strategy Challenge Fund
ISIS	ISIS Neutron and Muon Source
JASMIN	Joint Analysis System Meeting Infrastructure Needs
JET	Joint European Torus
LEAPS	League of European Accelerator-based Photon Sources
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty experiment
LIDAR	Light Detection and Ranging
MAST	Mega Amp Spherical Tokamak
MONSooN	Met Office/NERC Superco(o)mputer Nodes
MR Linac	Magnetic Resonance Linear Accelerator
MRC	Medical Research Council
MRI	Magnetic Resonance Imaging
MW	Megawatt
NAMRC	Nuclear Advanced Manufacturing Research Centre
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NHS	National Health Service
NiCoLA-B	AstraZeneca's drug discovery robotics platform
NIHR	National Institute for Health Research
NMR	Nuclear Magnetic Resonance
NNL	National Nuclear Laboratory
NOC	National Oceanography Centre
NPL	National Physical Laboratory
NRF	National Research Facility
OECD	Organisation for Economic Co-operation and Development
ORE	Offshore Renewable Energy
PET	Positron Emission Tomography
PRACE	Partnership for Advanced Computing in Europe
PSREs	Public Sector Research Establishments
PV	Photovoltaic
PWR	Pressurised water reactor
R&D	Research and Development
RACE	Remote Applications in Challenging Environment
RAL	Rutherford Appleton Laboratory
RCaH	Research Complex at Harwell
RIKEN	Rikagaku Kenkyūjo (Japanese Research and Development Institute)
RRS	Royal Research Ship
RUEDI	Relativistic Ultrafast Electron Diffraction and Imaging
SAMS	Scottish Association for Marine Science
SBUK	Synthetic Biology UK
SKA	Square Kilometre Array
SME	Small and Medium sized Enterprises
SMR	Small modular reactor
SMR	Steam Methane Reforming
SNS	Spallation Neutron Source
SRS	Synchrotron Radiation Source
STAR-IDAZ	International Research Consortium on Animal Health
STEP	Spherical Tokamak for Energy Production
STFC	Science and Technology Facilities Council
SUPERGEN	Sustainable Power Generation and Supply initiative
TfL	Transport for London
TRL	Technology Readiness Level
TROPOMI	Tropospheric Monitoring Instrument
UAV	Unmanned Aerial Vehicle
UCL	University College London
UKCRIC	UK Collaboratorium for Research on Infrastructures and Cities
UKDS	UK Data Service
UKGEOS	UK Geoenergy Observatories
UKRI	UK Research and Innovation
UK-RIHS	UK Research Infrastructure for Heritage Science
UKSA	UK Space Agency
UN	United Nations
UUV	Unmanned Underwater Vehicle
V&A	Victoria and Albert Museum
WHO	World Health Organisation
XAFS	X-ray Absorption Fine Structure
XFEL	X-ray Free Electron Laser

References

1 Department for Business, Energy & Industrial Strategy, International comparative performance of the UK research base, 2019 (website accessed July 2019)
2 Institute for Scientific Information, The Annual G20 Scorecard – Research Performance 2019, 2019 (website accessed July 2019)
3 Economic Insight, What is the relationship between public and private investment in science, research and innovation?, 2015 (website accessed April 2019)
4 Estimate from UK Research and Innovation economic models (unpublished)
5 McKinsey Global Institute, Global Growth: Can Productivity Save the Day in an Aging World?, 2015
6 Beagrie, C, The Value and Impact of the European Bioinformatics Institute, 2016 (website accessed May 2019)
7 Cambridge Policy Consultants, Socio-economic impact of EPSRC's investment in research equipment, 2018 (website accessed April 2019)
8 Technopolis Group, ISIS Lifetime Impact Study, Volume 1: Full Report, 2016
9 National Audit Office, BIS's capital investment in science projects, 2016 (website accessed May 2019)
10 Department for Business, Energy and Industrial Strategy, Industrial Strategy: building a Britain fit for the future, 2017 (website accessed April 2019)
11 Royal Society, Dynamics of data science skills - How can all sectors benefit from data science talent?, 2019 (website accessed June 2019)
12 TechHQ, Investment in UK artificial intelligence startups soars, 2019
13 UK Research and Innovation, Pathways to 2.4%: evidence and analysis to inform the development of the Government roadmap, 2019
14 Ministry of Defence, Global Strategic Trends The Future Starts Today (6th Edition), 2018 (website accessed May 2019)
15 Elsevier, Performance of the UK research base: international comparison, 2016, 2016
16 Cornell University, INSEAD, and the World Intellectual Property Organization, Global Innovation Index (GII) 2019: Creating Healthy Lives-The Future of Medical Innovation, 2019 (website accessed July 2019)
17 Eurostat Statistics Explained, R&D expenditure (data extracted 2018).
18 UK Research and Innovation Infrastructure Roadmap Programme, Landscape Analysis, 2019
19 Main Science and Technology Indicators, OECD MSTI database (data extracted 4 November 2018).
20 Xinhua, China issues S&T development guidelines, 2016 (website accessed April 2019)
21 Eurostat Statistics Explained, Archive: Europe 2020 indicators – research and development, 2016 (website accessed April 2019)
22 Science Mag, Trump, Congress approve largest U.S. research spending increase in a decade, 2018 (website accessed April 2019)
23 European Strategy Forum on Research Infrastructures, The National Roadmaps, 2019 (website accessed April 2019)
24 Research Councils UK, RCUK Strategic Framework for Capital Investment, 2012 (website accessed April 2019)
25 Department for Business, Energy and Industrial Strategy, Research and Innovation Organisations in the UK, 2015 (website accessed April 2019)
26 Research Councils UK, Large Facilities 2010, 2010 (website accessed April 2019)
27 Royal Society, A snapshot of UK research infrastructures, 2018 (website accessed April 2019)
28 Department for Business, Energy and Industrial Strategy, BIS science capital roadmap, 2014 (website accessed April 2019)
29 European Strategy Forum on Research Infrastructures, ESFRI Roadmap, 2018 (website accessed April 2019)
30 House of Lords, House of Lords Science and Technology Committee inquiry on Scientific Infrastructure, 2014 (website accessed April 2019)
31 European Commission, About Research Infrastructures (website accessed Nov 2018)
32 UK Research and Innovation Infrastructure Roadmap Programme, Initial analysis of infrastructure questionnaire responses and description of the landscape, 2018 (website accessed April 2019)
33 UK Research and Innovation, UK Research and Innovation Delivery Plans 2019 (website accessed April 2019)

34 UK Research and Innovation Infrastructure Roadmap Programme, Progress Report, 2019 (website accessed April 2019)
35 Office for Life Sciences, Bioscience and Health Technology Sector Statistics 2018, 2019
36 Office for Life Sciences, Life sciences: industrial strategy, 2017 (website accessed May 2019)
37 Department for Business, Energy & Industrial Strategy, Bioeconomy strategy: 2018 – 2030, 2018 (website accessed May 2019)
38 Department for Business, Energy & Industrial Strategy, The Clean Growth Strategy: Leading the way to a low carbon future, 2017 (website accessed May 2019)
39 Animal and Plant Health Agency, APHA Science Strategy 2015-2020, 2015
40 Medical Research Council, Maximising the value of UK population cohorts: MRC Strategic Review of the Largest UK Population Cohort Studies, 2014
41 Biotechnology and Biological Sciences Research Council, Research in Agriculture and Food Security, Strategic Framework, 2017
42 Biotechnology and Biological Sciences Research Council, Economic and Social Research Council and Medical Research Council, A Cross-Council vision for Food, Nutrition and Health research, 2015
43 HM Government, A UK Strategy for Agricultural Technologies, 2013 (website accessed May 2019)
44 Designing Future Wheat, Homepage, 2019 (website accessed April 2019)
45 Department for Business, Energy & Industrial Strategy, The Clean Growth Strategy: Leading the way to a low carbon future, 2017 (website accessed May 2019)
46 Wilkinson, M. D et al., The FAIR Guiding Principles for scientific data management and stewardship, 2016 (website accessed May 2019)
47 Department for Business, Energy & Industrial Strategy, Introduction to Sector Deals, 2018 (website accessed May 2019)
48 Payne, D, Roadmap for Photoelectron Spectroscopy, Engineering and Physical Sciences Research Council, 2017
49 Department for Business, Energy and Industrial Strategy, Made Smarter Review, 2017
50 UK National Quantum Technologies Programme, A roadmap for quantum technologies in the UK, 2015
51 Government Office for Science, The Quantum Age: technological opportunities. Blackett Review, 2016
52 Science and Technology Facilities Council, Breast cancer detection research receives STFC funding, 2018
53 Engineering and Physical Sciences Research Council, Roadmap: Provision of Internationally Leading Wind Tunnel Infrastructure, 2015
54 Bolton, A et al., The Gemini Principles, 2018
55 Government Office for Science and Cabinet Office, Areas of Research Interest, 2017
56 UK Research and Innovation, Eligibility for Research Council Funding, 2016
57 UK Data Forum, UK Strategy for Data Resources for Social and Economic Research 2013 – 2018
58 Administrative Data Taskforce, The UK Administrative Data Research Network: Improving Access for Research and Policy, 2012
59 Economic and Social Research Council, Longitudinal Studies Review 2017, 2018
60 Welsh Government, Nest: Helping you make your home warmer and more energy efficient (website accessed March 2019)
61 Welsh Government, The Fuel Poverty Data Linking Project Findings Report No. 1: Initial Findings on the Impact on Health of the Warm Homes Nest Scheme, 2017 (website accessed March 2019)
62 Jefferies, B.J., Power, C and Manor, O, Alcohol consumption in two British Birth cohorts: from adolescence to adulthood. A report to the Strategy Unit (Cabinet Office), 2002
63 HM Government, The Government's Alcohol Strategy, 2012 (website accessed June 2019)
64 National Institute for Health and Care Excellence, Alcohol-use disorders: prevention – Public health guideline [PH24], 2010
65 Department for Children, Schools and Families, Draft Guidance on the Consumption of Alcohol by Children and Young People from the Chief Medical Officers of England, Wales and Northern Ireland, 2009 (website accessed June 2019)
66 The Fitzwilliam Museum, Nespawershefyt's coffin set (website accessed May 2019)
67 Department for Business, Energy & Industrial Strategy, Creative Industries Sector Deal, 2019
68 Design Council, The Design Economy: The value of design to the UK (website accessed May 2019)

69 PWC, UK entertainment and media sector to be worth £72bn by 2021, according to new PwC report, 2017 (website accessed May 2019)
70 Historic England, Heritage and the Economy 2018, 2018
71 Department for Culture, Media & Sport, Trends Business Research Ltd, NEF Consulting Ltd and Middlesex University, The role of culture, sport and heritage in place shaping, 2017
72 Age UK, Creative and Cultural Activities and Wellbeing in Later Life, 2018 (website accessed May 2019)
73 Facer, K and Enright, B, Creating Living Knowledge: The Connected Communities Programme, community university relationships and the participatory turn in the production of knowledge, 2016, Bristol: University of Bristol/AHRC Connected Communities (website accessed May 2019)
74 National Heritage Science Forum, Strategic Framework for Heritage Science in the UK 2018 - 2023, 2018 (website accessed May 2019)
75 Europeana, Homepage (website accessed June 2019)
76 Department for Business, Energy & Industrial Strategy, Offshore wind Sector Deal, 2019
77 HM Government, Nuclear Sector Deal, 2018
78 Ricardo Energy and Environment for the Committee on Climate Change, UK business opportunities of moving to a low carbon economy, 2017
79 The Energy Innovation Board, 2019 Energy Innovation Needs Assessments. [expected publication date 2019]
80 Mission Innovation, Homepage (website accessed May 2019)
81 Department for Business, Energy and Industrial Strategy, Clean Growth: Transforming Heating, 2018
82 Energy Systems Catapult, Local Area Energy Planning: Insights from three pilot local areas, Executive summary, 2018
83 Energy Systems Catapult, Local Area Energy Planning: key to minimising decarbonisation costs, 2018
84 Newcastle University, Integrel Briefing Note (website accessed June 2019)
85 The European Marine Energy Centre, Pathway to commercialisation - An EMEC guide to research, development and testing of marine energy technology, 2019
86 Nuclear Innovation and Research Advisory Board, NIRAB Annual Report 2018/19: Clean Growth through Innovation – the need for urgent action, 2019
87 Orion Innovations (UK) Ltd, A UK Vision for Carbon Capture and Storage, 2013 (website accessed May 2019)
88 International Energy Agency, Carbon Capture and Storage: Progress and Next Steps, 2010 (website accessed May 2019)
89 Simon Hettrick, It's Impossible to conduct research without software, say 7 out of 10 UK researchers, Software Sustainability Institute, 2014
90 Simon Hettrick, £840 million: the UK's investment in software-reliant research in 2013, Software Sustainability Institute, 2014
91 Hamilton, M et al, UK National E-Infrastructure Survey 2015 Report, High Performance Computing – Special Interest Group, 2015
92 Government Office for Science, Council for Science and Technology, Computational modelling: Technological Futures, 2018
93 Technopolis, Hartree Centre Phase 1&2 Baseline Evaluation: Final Report, 2018
94 Professor Dame Wendy Hall and Jérôme Pesenti, Growing the artificial intelligence industry in the UK (website accessed May 2019)
95 Engineering and Physical Sciences Research Council, EPSRC strategy for the developing landscape of Tier-2 HPC in the UK (website accessed May 2019)
96 Partnership for Advanced Computing in Europe, The Scientific Case for High Performance Computing in Europe 2012 – 2020: From Petascale to Exascale, 2012 (website accessed May 2019)
97 Physics, Synopsis: Peering into a Molecular Magnet, 2017
98 Engineering and Physical Sciences Research Council, National Research Facilities (website accessed Nov 2018)
99 UK National Crystallography Service, Homepage (website accessed Nov 2018)
100 Department for Business, Energy & Industrial Strategy, International Research and Innovation Strategy, 2019 (website accessed May 2019)

101 University of Nottingham, Sir Peter Mansfield Imaging Centre, The UK7T Network: developing the ultra-high field MRI platform for biomedical research (website accessed June 2019)
102 Department for Business, Energy and Industrial Strategy, Science and Innovation Audits (website accessed April 2019)
103 Department for Business, Innovation and Skills, Business-university collaboration: the Wilson review, 2012 (website accessed May 2019)
104 Department for Business, Innovation and Skills, Encouraging a British invention revolution: Sir Andrew Witty's review of universities and growth: final report and recommendations, 2013 (website accessed May 2019)
105 UK Research and Innovation, Strength in Places Fund (website accessed April 2019)
106 Belmana and Centre for Enterprise and Economic Development Research, Middlesex University, Interim Evaluation of the UK Research Partnership Investment Fund, 2018 (website accessed May 2019)
107 Medical Research Council, Clinical Research Capabilities and Technologies Initiative (website accessed May 2019)
108 Universities UK, Efficiency, effectiveness and value for money, 2015 (website accessed May 2019)
109 BioImagingUK, Homepage (website accessed May 2019)
110 League of European Accelerator-based Photon Sources, Homepage (website accessed May 2019)
111 Science & Technologies Facilities Council, Bridging for Innovators (B4I) funding (website accessed May 2019)
112 Equipment Data, About this site (website accessed May 2019)
113 Konfer, Homepage (website accessed May 2019)
114 Royal Academy of Engineering, Late-stage development and demonstrators (website accessed April 2019)
115 Armstrong, H and Rae, J, A working model for anticipatory regulation, 2017 (website accessed May 2019)
116 Browning, N and Hardwick, L, Identifying Infrastructure and Collaborative Expertise for Electrochemical Energy Storage Applications, University of Liverpool, 2018 (website accessed April 2019)
117 Knowledge Transfer Network, UK-Wide Capability Mapping of Industrial Digitalisation Technologies (IDTs), 2019 (website accessed April 2019)
118 Analysis by UK Research and Innovation using The Organisation for Economic Co-operation and Development data, 2018 (website accessed April 2019)
119 Department for Education and Higher Education Statistics Agency, Higher Education Staff: 2017 to 2018 academic year, 2019 (website accessed April 2019)
120 The Gatsby Charitable Foundation, Raising the profile of technicians (website accessed April 2019)
121 Russell Group, Impact of Brexit on the Technical Workforce, 2017 (website accessed April 2019)
122 European Commission, Report on the Consultation on Long Term Sustainability of Research Infrastructures, 2016 (website accessed April 2019)
123 Biotechnology and Biological Sciences Research Council, Non-faculty Researchers Survey, 2015 (unpublished)
124 Ball, M., Hardwick, R and Vere, K, Forge a clearer path for technical careers, 2016 (website accessed April 2019)
125 Technicians, Homepage (website accessed May 2019)
126 Technical Development & Modernisation, About the TDM Toolkit (website accessed May 2019)
127 Higher Education and Technician's Educational Development (HEaTED), Homepage (website accessed May 2019)
128 UK Research and Innovation, RCUK Statement of expectations for technology / skills specialists (website accessed May 2019)
129 University of Bristol, Career Framework for Technical Staff, 2017 (website accessed April 2019)
130 Open Data Institute, Data trusts: lessons from three pilots, 2019 (website accessed April 2019)
131 Wilkinson, M et al., The FAIR Principles for scientific data management and stewardship, Nature, 2016
132 UK Research and Innovation, Common principles on data policy (website accessed May 2019)
133 Higher Education Funding Council for England, Research Councils UK, Universities UK and Wellcome, Concordat on Open Resarch Data, 2016 (website accessed May 2019)
134 Archaeology Data Service, Homepage (website accessed May 2019)

135 Synchrotron Radiation Source, After two million hours of science a British world first bids farewell (website accessed May 2019)
136 Science & Technology Facilities Council, New Light on Science The Social & Economic Impact of the Daresbury Synchrotron Radiation Source, (1981 - 2008), 2008
137 Organisation for Economic Co-operation and Development, Reference framework for assessing the scientific and socio-economic impact of research infrastructures, 2019 (website accessed April 2019)
138 European Commission, FenRIAM: Proposal for a foresight-enriched Research infrastructure Impact Assessment Methodology, 2011 (website accessed April 2019)
139 European Commission, Interim Evaluation of the European Research Infrastructures including e-Infrastructures in Horizon 2020, 2017 (website accessed April 2019)
140 Department for Business, Energy and Industrial Strategy, Evaluation Plan 2016 (Annual Update to Annex A in the Evaluation Strategy), 2016 (website accessed April 2019)
141 HM Treasury, The Green Book: central government guidance on appraisal and evaluation, 2018 (website accessed April 2019)
142 HM Treasury, The Magenta Book: central government guidance for evaluation, 2011 (website accessed April 2019)
143 HM Treasury, The Aqua Book: guidance on producing quality analysis for government, 2015 (website accessed April 2019)
144 Department for Business, Energy and Industrial Strategy guidance [internal only]
145 Technopolis Group, International Comparative Study: Appraisal and Evaluation Practices of Science Capital Spending on Research Infrastructures, 2017 (website accessed April 2019)
146 European Strategy Forum on Research Infrastructures, Public Roadmap 2018 Guide, 2016 (website accessed April 2019)

UK Research and Innovation