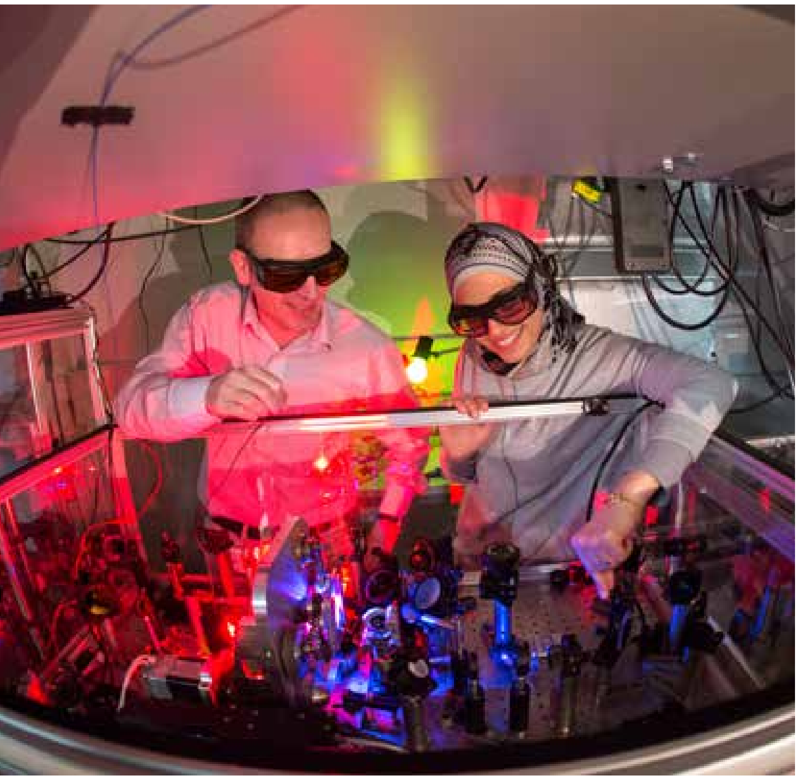
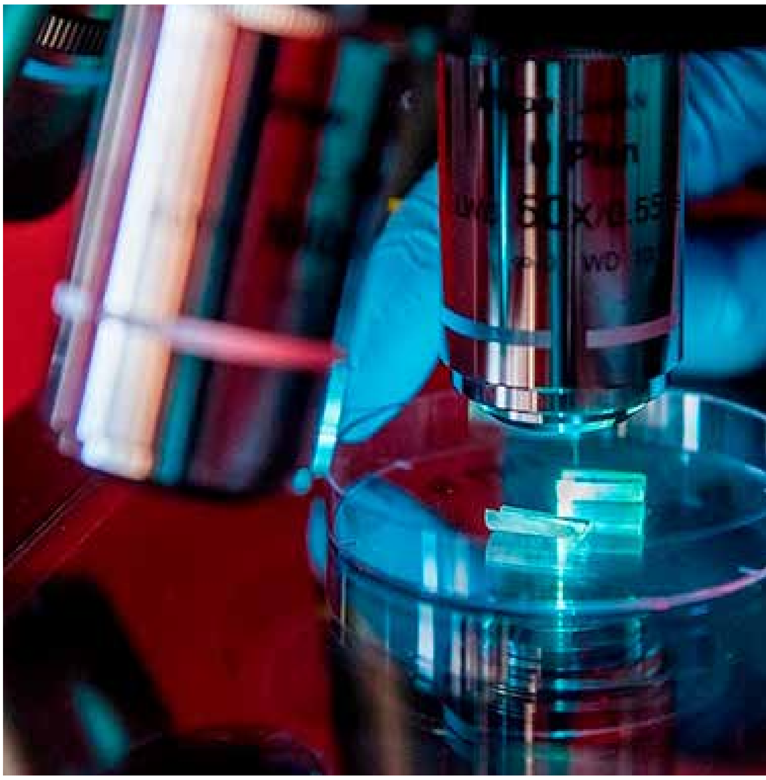
UK Research
and Innovation

UKRI Infrastructure Roadmap Progress Report





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Front cover image credits: top – STFC \ Hartree Centre, bottom left – Imperial College London, bottom right – University of Southampton

Foreword

Research and innovation are at the heart of the Government's modern Industrial Strategy which sets the ambition to raise total R&D investment to 2.4% of GDP by 2027, and 3% in the longer term. Achieving this ambition would realise a step-change in the UK's investment in R&D, the biggest increase since records began and it is vital that we capture the full range of economic, social and environmental benefits from this increase. To deliver the ambitious 2.4% commitment and the vision for our country set out in the Industrial Strategy, UKRI is working with partners across Government. The research and innovation infrastructure roadmap programme is designed to contribute to these key aims alongside work within UKRI and its councils to further develop its forward strategy[1]. The roadmap will increase our understanding of the UK's current capability and guide future planning.

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. It supports research and innovation activity at all scales, contributing to local and national economies and generating knowledge and capability critical to UK policy, security and well-being.

This research and innovation infrastructure is not only funded through UKRI and its councils. Several public, private and charitable 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 is a progress report presenting a summary of our work to date. It draws from our survey work with existing infrastructures, consultation workshops with stakeholders and the extensive advisory networks within the organisations involved. Alongside the Initial Analysis of Infrastructure Questionnaire Responses and Description of the Landscape[2] it seeks to build on previous work within funding bodies and disciplinary groups

identifying emerging themes and areas of potential capability which are common across the diverse capabilities of the UK. This report does not seek to make specific proposals or judgements on funding of particular infrastructures, rather the aim is to explore areas of capability and opportunity which can be further developed.

The programme is an ambitious one as the UK has never undertaken an exercise of this scale before. We recognise that it has not been possible to capture everything we would like within the time and are grateful for the input many expert stakeholders have given to the process so far. We hope that sharing the emerging findings now will support and encourage continued conversations about areas of future opportunity for the UK as we prepare the final roadmap. The next step will be to take the themes and issues identified here and develop them with continued input from the research and innovation community identifying any major themes not yet captured and opportunities for further connections across the landscape. The final report will set out options for how the potential capabilities described in this report might be achieved. We plan to publish this first edition of the roadmap in summer 2019.

Professor Mark Thomson

Executive Chair STFC and Senior Responsible Officer for the UKRI Infrastructure Roadmap Programme

Executive summary

This is a progress report presenting a summary of work to date. It draws on survey work with existing infrastructures, previous work in discipline areas and consultation workshops with stakeholders as well as the extensive advisory networks within the organisations involved. It seeks to identify emerging themes and areas of potential capability but does not make specific proposals or judgements on how to deliver these or the funding of particular infrastructures. The aim is to set out areas of capability and opportunity which could be further developed in the final roadmap. The next step will be to take the themes and issues identified here and develop them with continued input from the research and innovation community identifying any major themes not yet captured.

Our Industrial Strategy sets out how we are building a Britain fit for the future. To achieve this, we must ensure every part of our country realises its full potential and makes the most of our strengths so that we can be at the forefront of emerging technologies and industries in the years ahead, boosting productivity and earning power across the country. Research and innovation infrastructures contribute significantly across the framework set out in our modern Industrial Strategy (figure 1).

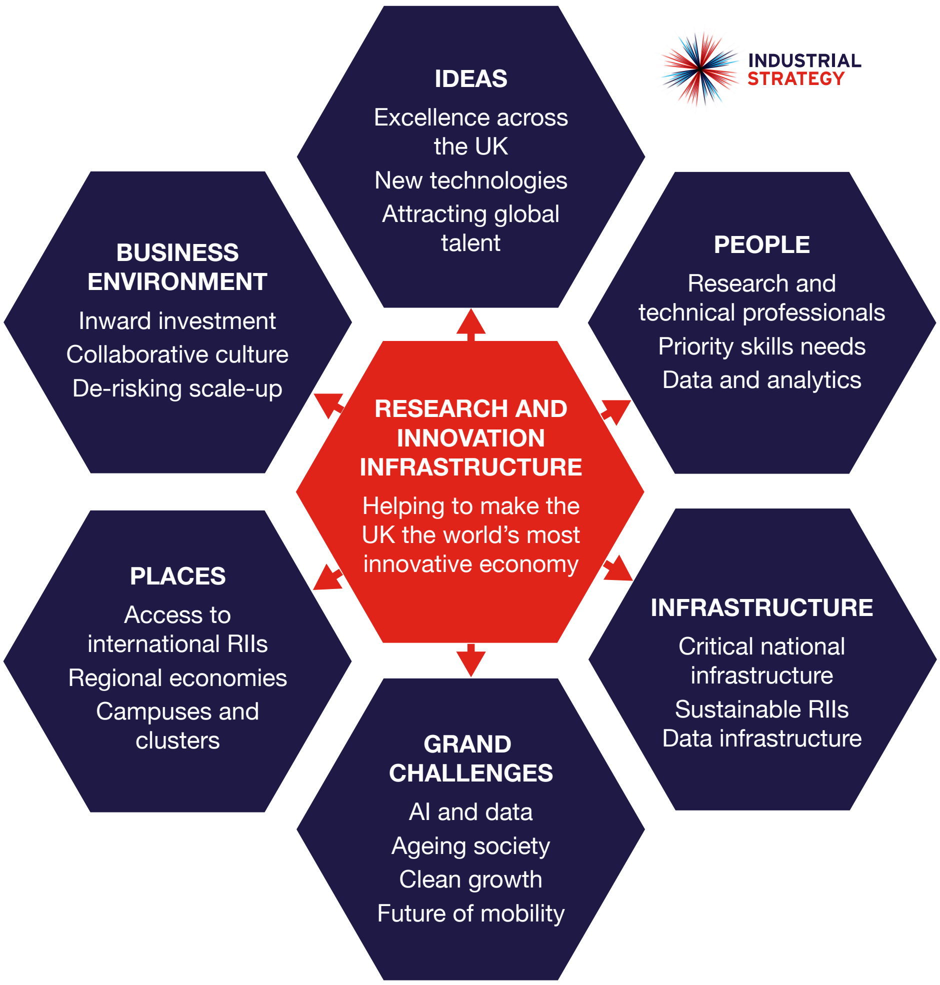


Figure 1: The Industrial Strategy sets the ambition for the UK to be the world's most innovative economy. Research and innovation infrastructures contribute across the strategy and to each of the Grand Challenges.

The UK's internationally-competitive research and innovation infrastructure, developed over many decades, already contributes significantly to the UK's world-leading performance in science, research and innovation. Its continued development will support the achievement of stretching commitments in this area to become the world's most innovative economy, including increasing the UK's total expenditure on research and development to 2.4% of GDP by 2027, 3% in the longer term. Achieving this ambition would realise a step-change in the UK's investment in R&D, the biggest increase since records began and it is vital that we capture the full range of economic, social and environmental benefits from this increase.

Access to world-leading infrastructure supports research and innovation activity on a variety of scales, from individual investigators to large multinational collaborations and across all industrial sectors.

The Industrial Strategy sets out the importance of building innovation excellence across all parts of the UK, capitalising on our existing strengths and fostering local ecosystems that can support innovation and sustained growth. The development of this roadmap can inform localised planning work through a greater understanding of how this landscape might develop over time.

Research and innovation infrastructures act as magnets for talent and investment from both domestic and international businesses and provide critical infrastructure to support de-risking of innovative business ideas or to support wider policy objectives. They also contribute to their local and regional economies through employment, often at the heart of localised clusters of expertise, and play a vital role in the training and development of specialist skills.

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 well-being. The Industrial Strategy identified four global Grand Challenges where the UK will build on our strengths to put us at the forefront of the industries of the future: putting the UK at the forefront of the artificial intelligence 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. Aligning our R&D infrastructure behind the Grand Challenges will be key to delivering these and attracting world-class talent and investment.

Recent investments through the £1.7bn Industrial Strategy Challenge Fund and other funds are creating nationally important infrastructures in support of these priority areas such as the UK Battery Industrialisation Centre in Warwickshire, Vaccines Manufacturing Innovation Centre in Oxford, National Satellite Test Facility at Harwell and infrastructure based at the National Innovation Centre for Ageing in Newcastle. We will ensure the UK R&D infrastructure is pulling together to deliver the Grand Challenges and enabling interdisciplinary collaborations to find solutions to these global transformations. The detailed chapters of this report also highlight where research and innovation infrastructures have the potential to contribute further to the Grand Challenges and Industrial Strategy Sector Deals.

Our engagement work to date identifies critical themes for the roadmap:

- Research and innovation infrastructures are long-term investments. They need to be sustainable not just in terms of funding but also as organisations, maintaining and evolving their technical and staff expertise as user needs change and in response to new technologies. **Sustainability and development challenges** need addressing with a focus on the whole lifecycle of an infrastructure.

- **Skills needs** are becoming an increasing challenge. In particular, the role of research technical professions and other specialist professions as part of wider research teams and the growing need for data scientists and related skills.

- **Although this programme focuses on larger scale infrastructures these are connected to the wider landscape**, including international collaborations, local clusters and virtual or distributed facilities. Ensuring these connections are in place and understanding the complementary roles of these different infrastructures has the potential to increase efficiency and effectiveness across the landscape and inform the development of related priorities such as Local Industrial Strategies in places across England.

- The increasing **need for multi and interdisciplinary working** is core to UKRI's mission. Many infrastructures exemplify this and there is potential to create even greater links between them where capability developed within one sector has the potential to create a step change in other sectors.

- All sectors face **common technical challenges or disruptors**. Key challenges are the increasing volume of **data, integration, modelling and simulation and implications of AI and machine learning** (one of the Industrial Strategy Grand Challenges). This is already changing the way research and innovation works. The lab of the future will require fundamentally new techniques, skills, ways of working and a change to the research culture.

- Developing the UK's **e-infrastructure** in response to changes in technology and increasing demand is vital. This includes networks, data infrastructure, access mechanisms, hardware and software development. We have the opportunity to plan any future approach in a strategic way.

- The **need to work at scale** to deliver a step change in capability is a common theme across the sectors. The increasing need to link data, develop demonstrators, living labs and other ways to integrate understanding and understand how ideas may work in practice. This fosters innovation and helps bridge the gap to application.

- The complexity of infrastructures and the challenges we face require close **working in partnership** with charities, industry, government and internationally. The support and goodwill from public service organisations and members of the public are also essential to many infrastructures.

This report sets out emerging themes and areas of potential infrastructure capability across the research and innovation landscape which we will test and develop further in the next phase of the programme. The Programme will further consult with relevant stakeholders in developing the final roadmap which will set out more detail on how the potential capabilities might be achieved and opportunities for future synergies across the infrastructure landscape. This report has been prepared by UKRI with support and advice from the following organisations: the 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, Higher Education Funding Council for Wales (HEFCW), Scottish Funding Council (SFC), Department for the Economy of Northern Ireland (DFE NI), the Royal Society, Universities UK and Association for Innovation, Research and Technology Organisations (AIRTO).

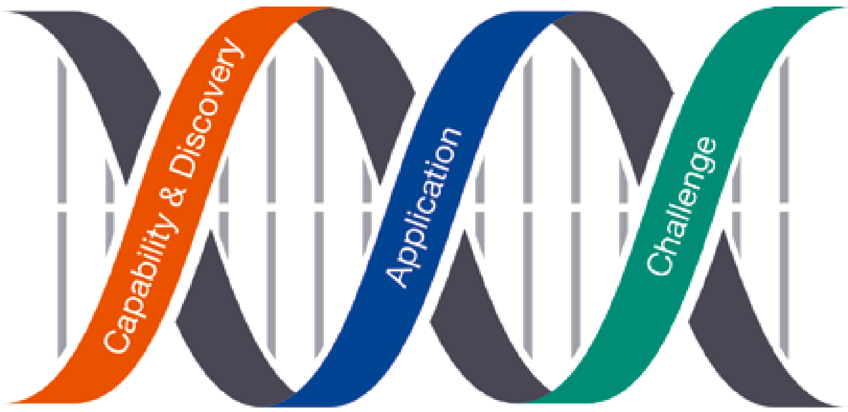
Chapter 1: Purpose of the infrastructure roadmap programme

Many OECD countries develop research infrastructure roadmaps as tools to support strategic planning. The UK has also undertaken roadmapping and prioritisation exercises in recent years[3,4,5,6,7], taking an active part in the European Strategy Forum on Research Infrastructures (ESFRI) prioritisation process for pan European infrastructures[8]. 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[9] and the National Audit Office[10].

The objective of the UKRI 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 UKRI'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 achieve 2.4% of GDP invested in R&D by 2027

Ultimately, future funding to develop existing infrastructures or create new capability will be dependent on strategic investment decisions from a range of organisations including the government and UKRI. This programme is not a funding programme but we hope the final roadmap guides this decision making and identification of priorities.



Capability and discovery driven infrastructures provide the fundamental capability that allows us to conduct discovery research.

Application driven infrastructures have an identifiable relevance to industrial sectors or other end-user groups within the economy. The complexity of the user problems will often require these infrastructures to be used in concert with other infrastructures.

Challenge driven infrastructures tend to be part of wider initiatives targeted towards addressing major scientific, technical, innovation, societal or policy challenges which directly address government priorities. They often build on outstanding, existing capability, which has been built up over many years.

Figure 2: Research and innovation infrastructure may have different primary functions but are interconnected.

Scope and definition of research and innovation infrastructures

UKRI has been tasked with capturing both research and innovation infrastructure in recognition of the fundamental role this plays within the wider Industrial Strategy[11]. Our Initial Analysis of Infrastructure Questionnaire Responses and Description of the Landscape also shows the exceptional diversity of UK infrastructure capability across subject disciplines which makes UKRI uniquely placed to undertake this work.

The term 'infrastructure' can be interpreted in many ways. For the purposes of this programme we have adapted the definition used by ESFRI and the EU Framework Programme[12].

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.

We are considering infrastructure with a range of primary functions but recognise that this capability is interdependent and connected (figure 2).

For the first UK roadmap of this scale we are focusing our work on infrastructure funded largely through public sector research and innovation funders. This means we have not systematically captured capability funded solely through private or charitable means. However, we recognise that partnership with the charity sector, shared facilities with industry, and with public services such as the NHS are also vital to the UK and many existing collaborations and partnerships already draw on this capability. Subsequent iterations of the programme could develop this theme further. The case study below illustrates how providing access to private sector capability has the potential to create value.

Partnership between MRC and UCB poised to accelerate drug discovery

Global pharmaceutical company UCB has opened up access to their state-of-the-art core antibody discovery platform. This platform is capable of generating and screening vast amounts of antibody-producing B cells and then isolating the rare cells that generate antibodies with the properties required to inhibit disease targets. This allows scientists to interrogate the vastness of the immune repertoire on a scale that would be otherwise impossible. Antibodies have become hugely successful drugs; in 2017, five of the top eight best-selling drugs globally were antibodies, with a global market for monoclonal antibodies valued at more than £75 billion.

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 public sector research establishments. Often funded through core capital budgets of institutions or project specific grants, such equipment and facilities provide researchers with the essential tools and fundamentals of a 'well-found' research establishment.

We have structured the work under the broad sectors used by ESFRI to support alignment of activities. These are:

- Biological sciences, health and food
- Energy
- Environmental sciences
- Physical sciences and engineering
- Social sciences, arts and humanities
- Computational and e-infrastructures

Although many international roadmapping exercises have followed a similar approach, there is currently no commonly accepted definition of 'innovation infrastructure' and many interpretations have been used in work to date. Some consider innovation in its broadest sense including people, policies and processes, others focus more on physical buildings and assets[13,14,15]. For the purpose of this exercise we are focusing 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. For example, this may include infrastructure aimed primarily at industry and set up to explicitly foster and commercialise innovation, such as the Catapult Centres, Innovation and Knowledge Centres, Centres for Agricultural Innovation, Innovation Centres in Scotland, research and innovation campuses/infrastructure where academic researchers and business collaborate and innovation focused activities based within universities or public sector research establishments.

Further discussion on how the definition of infrastructure has been refined within particular sectors is set out in the relevant chapters and the initial analysis.

The purpose of the progress report

This progress report describes the emerging themes and areas of potential capability identified through consultations. It does not describe how these might be achieved in detail or make judgements on the funding of particular infrastructures. **The emerging themes and areas of potential capability presented here are not prioritised.** The next step will be to take the themes and issues identified here and develop them with continued input from the research and innovation community identifying any major themes not yet captured and opportunities for further connections across the landscape.

To ensure a longer-term perspective on UK needs we are seeking to capture both more developed ideas and areas which are considered vital to progress, but where our understanding of what is needed requires further exploration. This inevitably means some themes described in this report are more developed than others. We recognise there are gaps in this analysis which we will seek to address for the final report.

To develop the content of this report we have:

- Undertaken an analysis of the current UK research and innovation landscape[2]
- Drawn on existing literature and roadmaps within subject areas
- Explored future priorities through a range of workshops and interviews with different stakeholder communities from academia, business, charitable and public sectors alongside the existing advisory structures within UKRI and participating funders
- Drawn from parallel work and consultation informing the developing 2.4% roadmap and UKRI councils' Strategic Delivery Plans

It is well understood that many infrastructures work across sectors as well as within their discipline and face many common challenges. The following chapters set out a summary of findings to date both within each sector and looking across the landscape for systemic and cross cutting needs that will impact on all infrastructures regardless of subject focus, model of operation or user base.

Chapter 2: Strategic context

The Industrial Strategy[11] sets the ambition for the UK to be the world's most innovative economy and to raise total R&D investment to 2.4% of GDP by 2027. 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 well-being. This includes the Grand Challenges set out in the Industrial Strategy: putting the UK at the forefront of the artificial intelligence 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.

Our ability to innovate – to develop new ideas and deploy them – is one of Britain's great historic strengths, bringing significant benefit to the economy and society. The UK is the most productive science base in the G7 ranking first amongst comparable major research nations for Field Weighted Citations Impact (FWCI), a measure of research quality[16]. The UK also has the most productive research base in the G7 in terms of papers and citations per unit of R&D expenditure and ranks within the top four of the Global Innovation Index[17]. Every £1 spent on public R&D delivers approximately £7 of net economic benefit to the UK[18] and unlocks £1.40 of private R&D investment[19]. 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[20].

The UK's global stature in research and innovation is founded on the availability of internationally competitive infrastructure, as highlighted in UKRI's strategic prospectus[1]. Access to world-leading infrastructure supports research and innovation activity at all scales, from individual investigators to large multinational collaborations. Research and innovation infrastructures bring together talent from the public and private sectors and

ISIS Neutron and Muon Source delivers £1.4billion economic benefit

The ISIS Neutron and Muon source is expected to deliver £1.4 billion of net economic benefit based on its work to 2014, a return on investment of at least 214% and a further £1.4 billion of economic benefit is predicted up to 2030. ISIS is the world's leading pulsed neutron and muon source, allowing scientists from across the world and research disciplines to study materials at the atomic level. Applications have been wide ranging, from cleft palate treatment development to solutions for waste water management. The infrastructure has long established industrial links with more than 100 companies, including Rolls-Royce, Unilever, Airbus and BP and plays an important role in nurturing scientific and technical talent for the wider economy.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Estimated economic impacts of ISIS facility between 1985 and 2013 (Technopolis 2016)

ISIS facility economic impact, eg. employment	Spend by industrial/academic visitors to ISIS facility	Economic benefits attributable to ISIS-research	International investment into ISIS facility	Value of educational training at ISIS facility
£400m	£20m	£480m	£56m	£3m

Source: Technopolis (2016)

across disciplines to tackle society's most complex challenges. 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 well-being. Between 2015–2016 and 2020–2021 BEIS and UKRI have committed to spending over £7.5 billion of capital funding on research and innovation infrastructure. Additional investment is also provided through other government departments and through European programmes.

2.1 Drivers for change

Planning for infrastructure requires consideration and anticipation of the critical research and innovation questions often decades ahead. Infrastructures need to be agile to changes in technology, availability of new research methods and changes to research and innovation culture and practice. Some of the critical drivers for change raised through our landscape survey are listed below. These are not exhaustive but affect all sectors.

Developments in artificial intelligence (AI) and data science emerged as the technological changes with some of the greatest impact across the sectors. The government's Industrial Strategy[11] recognised this and the huge global opportunities presented. Complex AI applications rely on greater computing power, bandwidth and network speeds. AI (and subsets such as machine learning) optimises the use of data to model and predict or anticipate some aspect of the world.

Advances in robotics automation and remote access/control, can have significant impacts on the environment and culture within which people work. These changes could also impact on the way infrastructures are organised and managed. Coupled with advances in battery and power technology these innovations can make infrastructures faster and more efficient and be able to be deployed in more remote and extreme environments. Smart grids, which bring together sensing, automation and two-way communication capabilities to the power grid infrastructure will impact on the way we develop and operate infrastructures.

Advances in visualisation technologies such as the increased use of 3D and augmented reality (AR) also change the way we use 'big data'. Applications will impact infrastructures across sectors from medical imaging to materials science to the arts. Advances in sensing and imaging capabilities are also being achieved through developments in photonics and the use of quantum technologies (e.g. quantum sensors).

Open discovery or research refers to ideas of best research practice by opening access to results, data, protocols and other aspects of the research process. It also includes the use of open source software and open standards that offer unfettered dissemination of scientific discourse. The explosion in the use of social media and the rise in citizen science is also changing the way research is designed, conducted and in the type and volume of data collected.

The draft framework in figure 3 shows how existing strengths (e.g. infrastructure) enable drivers that push the frontiers of human knowledge (e.g. AI), which in turn contribute to economic, social and cultural impact. The thematic research and innovation areas are illustrative of current priorities but not intended to be comprehensive. The following chapters draw out many of these themes and the implications for future infrastructure capability.

Delivering UKRI's vision and the government target of 2.4% of GDP spent on R&I

Figure 3. Draft thematic framework of research and innovation. Enablers support drivers that push the frontiers of human knowledge, which deliver economic, social and cultural impact. This contributes to the UKRI vision outlined in the strategic prospectus and the government target of raising R&D investment to 2.4% of GDP. Thematic R&I areas are illustrative, not exhaustive.

Chapter 3: Critical policy and cross-cutting issues

This chapter sets out critical policy considerations and cross cutting issues which impact on both current and future infrastructures across all sectors. Although not an exhaustive list, the themes described below have been frequently raised by stakeholders as critical for future planning.

3.1 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. The factors affecting the sustainability and agility of research infrastructures have been explored extensively[9,21,22]. A critical underpinning factor is the **continued focus on excellence of research and innovation activities**, a core value for UKRI[1]. This attracts a wide range of users and partners which in turn maintains and further enhances the quality of outputs.

Consideration of the whole lifecycle of an infrastructure is important from the outset (see figure 4). In some disciplines this can take the form of clear stages of development, in others the process is more fluid as an infrastructure evolves over time. This lifecycle is not always fully taken account of by either the infrastructures themselves or facilitated by funding structures and planning processes[23].

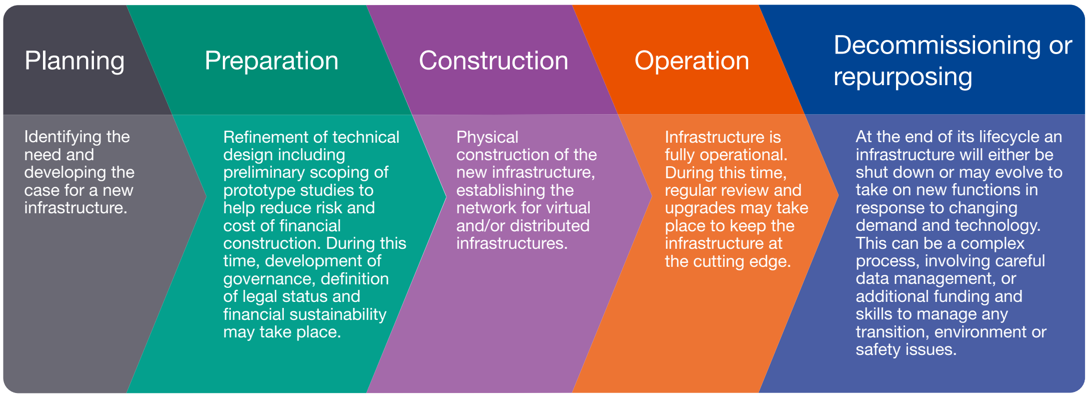


Figure 4. Key stages in the lifecycle of research and innovation infrastructures.

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 plan** are important to enable full benefits to be realised for users, potential co-funders and the wider economy. The challenge of reconciling the short-term funding periods and uncertainty beyond with a long-term plan was the most cited barrier to effective operations mentioned in responses to our landscape survey. Most respondees felt they were only able to plan one to three years ahead despite the long-term nature of their work. Any long-term commitment should be supplemented by a clear cycle of monitoring, review and performance evaluation to ensure quality and value for money is maintained. We need to remain flexible to respond to changing needs and new opportunities.

Most infrastructures operate in **complex funding landscapes drawing on multiple funding 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 operational funds may need to be drawn from elsewhere.

Predictable funding cannot be guaranteed for the full lifecycle given the many year duration of infrastructures. This can make it **challenging to ensure infrastructures are operating optimally, supporting long-term operations and ongoing technology development**, and tensions establishment of new capability against maintaining and developing existing infrastructures. These are common challenges for funders and infrastructures at all scales[9,24,25,26]. Creation and operation of infrastructures is inherently complex and almost always involves multiple funding streams. Decisions to fund new infrastructures should take account of the full lifecycle costs. This should include consideration of how future operations could be funded, whether there is sufficient demand for the infrastructure and strong governance and incentives to ensure efficient and effective use.

Many of the UK's existing infrastructures have complex operational models involving multiple partners. This can be a consequence of the scale of the undertaking, to support sustainability and to bring together unique combinations of expertise. UKRI and the organisations involved in the programme are not the only funders of infrastructure in the UK. Many of the future areas of capability described in this report would likely require **partnerships with others to realise the full ambition –** this could be between universities, public sector research establishments, governments, industry, charities and with investment from UK or overseas. Partnerships and collaborations can be through shared investment, new legal structures or in kind through access to equipment, data or other resources where partners have common goals.

The 5G Innovation Centre (5GIC) is the UK's largest academic 5G wireless communications infrastructure research centre established at the University of Surrey in 2015. It provides the world's leading open and independent testbed covering 4km^2 with indoor and outdoor environments for broadband mobile and the Internet of Things (IoT). Projects are already having an impact with an IoT system developed at the centre to monitor the homes of elderly patients successfully deployed to alert doctors and relatives in emergency situations. The centre was jointly funded through Research England's UK Research Partnership Investment Fund (UKRPIF) programme with co-investment from leading international telecommunications firms such as Vodafone, Telefonica, Huawei, Fujitsu and Samsung and from the Enterprise M3 Local Enterprise Partnership. To date every £1 invested through UKRPIF has leveraged £5.49 private and public investment and work conducted at the centre has led to over twenty UK, European and international patents. 5GIC's tiered membership has grown significantly and now includes all major network operators, hardware manufacturers and numerous SMEs enabling a wide range of businesses to take part in the growing mobile market.

A £170 million investment in **clinical research infrastructure** across the UK was made possible by partnership between the MRC, Department of Health, Wellcome Trust, CRUK, BHF and ARUK. The initiative has provided funding for new research technologies to advance the UK's ability to explore new areas for clinical research addressing a range of major health challenges such as dementia, cancer, metabolic disorders, arthritis and respiratory diseases[27].

3.2 Skills and training

The availability of specialised, skilled staff is also critical to the operation of infrastructures across all sectors. There is an increasing recognition that vital national infrastructures will not realise their potential without specialist, technical and analytical expertise. As well as developing and operating the infrastructures, such professionals perform vital roles in training others in their use, working alongside visiting research teams and developing new and transformative technologies or techniques.

However, the UK's population of 'research technical professionals' is ageing; research by the Gatsby Charitable Foundation suggests that the UK needs 700,000 more technicians by 2020[28] and the initial analysis illustrates the reliance on overseas expertise. Demand already exceeds supply in several areas where we are reliant on our ability to attract technical professionals, other specialists and research talent in a globally competitive market. Concerns over staff and skills shortages (particularly at mid-career stage), retention and succession planning were two of the top barriers to operation raised through our landscape survey. The demand for such skills will only become more acute in response to the emerging needs described throughout this report.

Analytical, data and knowledge management skills are increasingly in demand across all sectors. This ranges from specialists who can support the users of infrastructure through to raising general data literacy and skills in users. The need to manage, use and interpret large volumes of data has become an even more critical capability across all sectors with an increasing reliance on, and need for, managed services to process, store and analyse data.

European Commission analysis[29] has shown a long-term perspective and career track as key to increasing attractiveness of infrastructures as employers and could support the international mobility of '**technical professions and other essential specialists**'. At the institutional and national level the clarity of the career path for such professionals often remains unclear. Stakeholders tell us 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 through their overall contribution to the management of facilities and training of users[30,31].

Further work is needed to **develop career options, incentives and training needs** for these professions building on examples of good practice. UKRI has published the Statement of Expectations for technology/ skills specialists[32]. This sets out the expectations of research organisations, UKRI and individual technical staff to ensure parity of esteem between technical and academic staff, and access to improved career development and progression opportunities. An action plan is scheduled for 2019.

Research Software Engineer (RSE) Network

EPSRC has recognised the importance of investing in software development alongside research specialism through the creation of the RSE Network and Fellowships. In the past, software developers were hired into postdoctoral roles with an adverse effect on their career when they were judged on their papers, rather than their code. The RSE network and fellowships has helped raise awareness of this role and bring the community together, which has aided the development and retention of RSEs in academia to fulfil this critical research role.


STFC

Oxfordshire Advanced Skills (OAS)

OAS is a partnership between the UKAEA and the STFC to increase the number of trained technicians available to local Oxfordshire employers. Phase 1 is training around eighty apprenticeships with sixteen partner employers on board. A new centre at UKAEA's Culham site will welcome a larger intake in September 2019. Training provided by the Advanced Manufacturing Training Centre includes core engineering skills and the latest advanced manufacturing techniques used in industry. Engineering apprentices at STFC's Rutherford Appleton Laboratory spend their first year at OAS which equips them with foundation engineering skills they then build on during the rest of their four year apprenticeship.

3.3. International perspective

Research and innovation are international endeavours requiring sharing of knowledge, expertise, data and capability across organisations, borders and continents. As the landscape becomes increasingly interconnected, there is a **growing need to facilitate the transnational access to first-class research infrastructures**, to foster collaboration and optimise the use and impact of national infrastructures through international cooperation. Additionally, many research and innovation infrastructures are too big, complex or expensive for a single country to build and manage alone. The creation and maintenance of such infrastructures **requires strong partnerships between governments as well as academia**, giving these infrastructures an important role as part of the wider dialogue between countries.

Research and Innovation infrastructures in the UK have a strong and long history of international collaborations, which is set to continue and intensify. The UK is a major partner in many overseas infrastructures, e.g. the European Organization for Nuclear Research (CERN), home to the Large Hadron Collider, the world's largest and most powerful particle accelerator; the European Southern Observatory (ESO), which provides state-of-the-art research facilities to astronomers and astrophysicists; the European Molecular Biology Laboratory (EMBL), Europe's flagship laboratory for the life sciences; the European Synchrotron Radiation Facility (ESRF) which operates the most powerful high-energy synchrotron light source in Europe and the Institut Laue-Langevin (ILL), an international research centre which operates the most intense, reactor-based neutron source in the world.

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 new ESFRI Roadmap[8] launched in September 2018 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 in the Group of Senior Officials (GSO), established by the G8 Science Ministers in 2008 to informally explore cooperation opportunities in Global Research Infrastructures. GSO members are Australia, Brazil, Canada, China, the European Commission, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, UK and USA.

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. In doing this, it will be important to maintain and enhance our ability to attract infrastructure activity and skills into the UK. Following EU exit, the UK will seek to agree a far-reaching science and innovation agreement with the EU that establishes a framework for future collaboration, as announced in 'Collaboration on science and innovation – a future partnership paper'[33].

ELIXIR – a distributed infrastructure for life-science information

ELIXIR brings together life science data resources from 22 countries across Europe and EMBL, to manage and safeguard data through databases, software tools, cloud storage, supercomputers 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 on 'platforms', e.g. interoperability, or to work together to tackle challenges with far-reaching impacts. For example, the Human Protein Atlas resource is used 1.2 million times per year by scientists from 198 countries. ELIXIR contains a hub (at EMBL-EBI) and national nodes, with two nodes sited within the UK (EBI and the Earlham Institute), which unite UK resources in bioinformatics and computational biology at a national level.

Square Kilometre Array (SKA)

SKA Organisation

The SKA will be the world's largest 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. 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. 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.

3.4 Collaboration and connectivity of infrastructures

Research and Innovation infrastructures play an important role in **fostering a collaborative culture** in research and innovation. They provide a focal point to bring together diverse groups across the UK and internationally in both formal collaborations and informal networks. While this roadmap has been structured into sectors we recognise that as challenges become more complex there is a greater need for **multi and interdisciplinary working** and for researchers to access expertise from outside of their usual sector. The initial analysis demonstrates how many infrastructures already underpin research across multiple subject areas and economic sectors and there are opportunities to foster innovation by using technical capability developed in one discipline in new contexts.

Answering complex, interdisciplinary problems and addressing the challenges faced by UK business requires a combination of approaches and draws on infrastructures that operate at different scales, provide complementary expertise and different perspectives. Understanding and ensuring the **interconnectivity and complementary roles of these different types of infrastructure** supports effective development of overall UK capability. It can increase the productivity of investments and enhance the quality of research and innovation outputs.

Progress has been made to support **successful equipment sharing** initiatives[34,35,36,37,38] which have helped to develop institution-based and more **distributed networks of equipment and facilities** that are being managed as infrastructures. This networking approach supports investment in higher specification capability, enables a wider range of research and creates management efficiencies. It also ensures individual infrastructures and teams are better equipped to make best use of more specialist facilities. Such distributed networks of infrastructures can be seen collectively as national-level capability with each individual infrastructure also acting as critical localised capability.

The creation or upgrading of such distributed infrastructures are strategic investments for any funder and need to be co-created with the community to ensure priorities meet the evolving needs of different disciplines or industry sectors. However, funders can accelerate step changes in capability by encouraging communities to support the development of focused roadmaps. This can be in particular challenge areas, topics or methodological techniques and can capture the importance of investments at different scales.

Collaborative working to shape 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.

3.5 Clusters and local economies

'Place' is one of the five foundations of the government's Industrial Strategy. Clusters can play a role in local planning, including Local Industrial Strategies in England representing a critical mass of world-class expertise in the development and commercialisation of ground-breaking products, services and applications – expertise that businesses can tap into, add to and reinforce. The Science and Innovation Audits (SIAs)[39] show how research and innovation assets and capability can be a critical contributor to local economic development. UKRI's Strength in Places Fund[40] uses the evidence from the SIAs and other sources to understand where opportunities lie for investment in research and innovation to drive growth. This fund supports relative regional growth by identifying and supporting areas of R&D strength that are driving business clusters with innovation potential to become nationally and internationally competitive.

Clusters have a proven track record in opening up new markets, attracting business and academic expertise, providing opportunities for collaboration, co-operation, training, peer support and learning. They can help foster work across disciplines, cover a range of technology readiness levels (TRLs) and can help concentrate and accelerate the development of technology. They provide environments where organisations of all sizes can be part of dynamic, supportive innovation communities, enjoying ready access to the expertise and equipment they need to succeed. Clusters can emerge around universities, PSREs or groups of universities. Research and innovation campuses are also examples of such infrastructure such as Harwell, Daresbury, Culham, Babraham, Norwich, Easter Bush, Rothamstead and Aberystwyth.

Although not in scope for this programme, business incubators are also key elements of the wider innovation system[41]. They are often closely linked to infrastructures through co-location (for example the European Space Agency Business Incubation Centre UK at Harwell) or thematically (for example the Stevenage Bioscience Catalyst Accelerator).

3.6 Data

The government's Industrial Strategy recognises the importance of achieving a digitally connected economy that realises significant value from connected, large-scale data that can be rapidly analysed to generate insights and innovation. The opening up of government and private sector data and the advances in data analytics and associated technologies such as visualisation are also key to fostering a healthy innovation system. This explosion in 'big data' comes as the use of numerical and predictive simulations is expanding to allow for increased accuracy, longer timescales or across greater scales. The ability to effectively use and manage such large volumes of data is one of the critical challenges for current and future infrastructure planning. Advanced statistical techniques such as machine learning can be transformative but larger datasets will require advanced computing facilities to utilise to their maximum and, as discussed in section 3.2, need new skill sets which are already in short supply. The roadmap will be an opportunity for UKRI partners and others to adopt a more strategic and joined-up approach to these opportunities and challenges.

Open data: As technology advances, instrumentation outputs become larger and more complex and impact on mechanisms to store, manage and make the data available. Research and innovation 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 ready upload or download of data. Access to open data has benefits for researchers and business users. It also allows access to government, administrative and business data as well as data generated from academic experiments or studies. Recently, the government's Open Data Task Force has considered questions around open data in the research and innovation landscape, and UKRI will respond to those recommendations once the Task Force report is published later in 2018.

Managing 'big data': The increasing prevalence of 'big data' will require increases in computation, storage and networking capacity and speed, as well as the use of innovations such as deep learning to help optimise the use of the data. New funding models are required if the data is to be stored, accessed and analysed in the public cloud.

Data security and information governance: Information governance is a broad term spanning the security of e-infrastructure, the ethical use of data and the processes put in place to govern the digital information used daily by the UK's research and innovation communities. Research and innovation may require access to personal and sensitive data. For example, medical and personal records are important tools in medical, economic, social and population level research, and business-sensitive data underpins many economic analyses. Access to these data needs to be carefully managed by the data holders and data must be held in secure environments and managed to agreed standards. There are increasingly stringent compliance, governance and data security requirements, and we need increasingly sophisticated measures and tools to guard both the data and analytics processes from attacks, theft, or other malicious activities.

The Administrative Data Research Partnership

The newly-launched ADRP seeks to maximise the potential of administrative data as a resource for high-quality innovative research on critical policy issues for the UK. It will acquire, curate and provide a secure route for accredited researchers to use de-identified data from across government departments, local authorities and health authorities. ADRP is a partnership between UKRI, the Office for National Statistics (ONS), the UK Statistics Authority, National Statistical Institute and Devolved Administrations.

3.7 Partnerships and participation

The effectiveness of infrastructures often depends on support and goodwill from public service organisations and the public. Research in hospitals, schools, museums and other public services is vital for discovery research, applied studies and innovation. This may call for different uses of space, staff time, special governance and 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.

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 sciences 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.

The £16 million **Demonstrator Programme within the Robotic and AI challenge of the ISCF** was launched in 2017. The programme is supporting technical feasibility studies and experimental developments of robotic and AI systems to take humans out of dangerous, harsh or extreme working environments. Projects awarded so far include work on nuclear decommissioning, technologies to transform the delivery of logistics (jointly with DSTL and DfID) maintenance of off-shore wind turbines and deep sea technologies for autonomous exploration.

3.8 Demonstrators, test beds and 'living labs'

Many of the emerging priorities within this report show the need to test ideas at scale, show how technologies or data might integrate or how potential solutions might operate in the 'real world'. There are several types of infrastructures that can achieve this, and with the emphasis on increasing multi-disciplinarity to address real-world challenges, the demand for these types of infrastructure is likely to increase. For example:

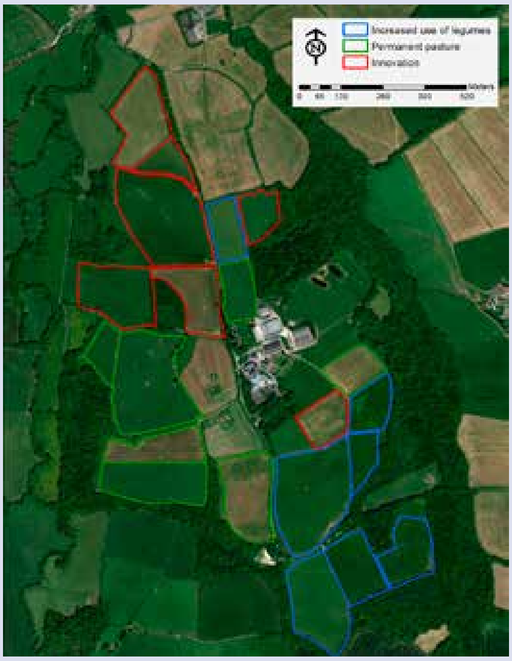
Demonstrators are near-market projects testing solutions in real-life conditions and taking a whole systems (cross-sectoral) approach to de-risking or scaling-up implementation of ideas. Given the cost and proximity to market they are often collaborations between public and private sectors.

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 academics, the public sector, industry and the third sector to work with users in co-designing, testing and implementing new services.

Living labs are user-centred and often based in a particular geographical location, e.g. city, agglomeration or region. They integrate concurrent research and innovation processes within a citizen-public-private partnership and may be critically dependent on the commitment and capacity of non-research organisations, such as hospitals, schools or local authorities. The concept is based on a systematic user-driven co-creation approach integrating research and innovation processes[42].

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 'green-engineer' solutions to flooding, efficient use of water resources and animal health.



3.9 Contribution to industrial sectors, policy challenges and statutory requirements

Many of the emerging themes in this report link to the development of key economic sectors, Sector Deals under the Industrial Strategy and other government policy priorities. New innovations and business opportunities may also arise through collaboration between suppliers and research teams through public procurement[43]. The landscape analysis shows how infrastructures are already working with businesses, government and other users across the UK economy to foster innovation and economic growth. Collaborative, two-way relationships between infrastructures and their users is vital to maximise value and identify potential areas of investigation. Recent investments include the creation of nationally important infrastructures such as the Catapult network, UK Battery Industrialisation Centre, Vaccines Manufacturing Innovation Centre and the National Satellite Test Facility through the ISCF.

Catapult network supports development of new products and services

The network of Catapult centres brings together UK businesses, scientists and engineers to work side by side on late-stage research and development, transforming high-potential ideas into new products and services to generate economic growth. The High Value Manufacturing Catapult's Composite Lightweight Automotive Suspension System (CLASS) project, led by Ford Motor Company in partnership with WMG, Gestamp Chassis and GRM Consulting, developed a new car chassis component to replace a multiple-piece fabricated steel component with a single moulding. This resulted in a weight saving in excess of 4.5kg per vehicle, a 35% saving on the current part and demonstrated the potential to reduce CO_2 emissions over the lifetime of the vehicle.

Supporting policy development and statutory requirements remains a priority for both the current and future infrastructure landscape. Alongside these contributions to public policy, some infrastructures also perform critical functions to support resilience and response to emergencies. Continuing to ensure this capability is available to the nation is an important priority and building links between infrastructures funded through UKRI and those funded by other government departments will become increasingly important.

Using cohort data to identify the risk from smoking

Data from the 1958 Birth Cohort on smoking behaviour in pregnancy first identified with confidence the correlation between smoking in pregnancy, birthweight and gestational age. This led doctors to change the advice given to pregnant women alongside a major public health campaign, with rates of smoking in pregnancy falling from 39% to 12% in subsequent years, dramatically reducing risks to thousands of pregnancies and babies .

British Film Institute National Archive

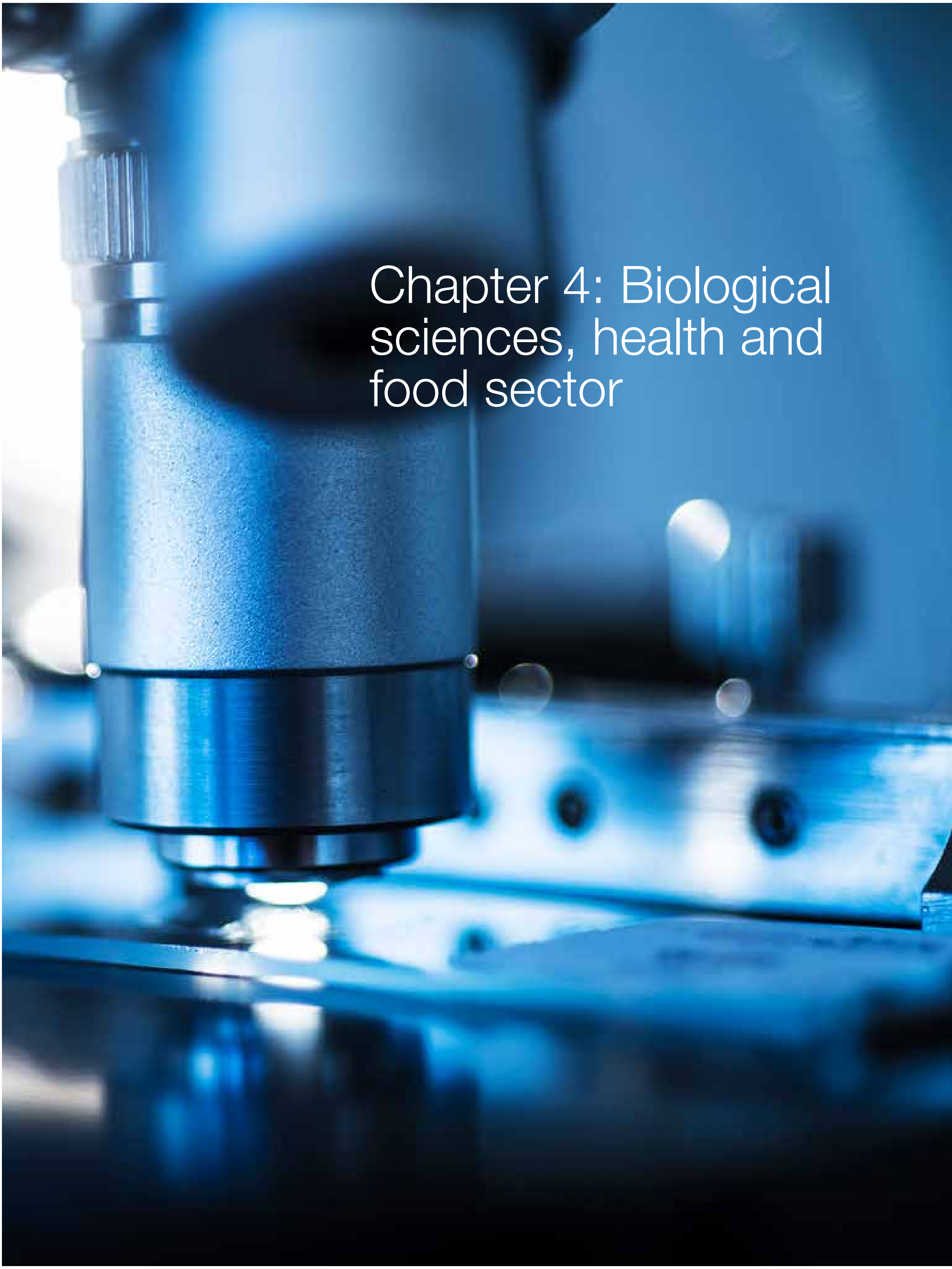
The AHRC funded Colonial Film Project produced an online catalogue showing life in the British colonies from 1895 to independence. It drew on film archives from three important infrastructures: the British Film Institute (BFI), Imperial War Museum and the British Empire and Commonwealth Museum. The BFI National Archive alone holds one of the largest film and television collections in the world. Established in 1935, the collection contains nearly a million titles dating from the earliest days of film to the live capture of current television content. The project has conserved a significant period of our global cultural heritage and made it internationally accessible. The project's website launch was accompanied by a commercial film season attended by over 1,000 paying viewers and led to a new, two-month exhibition at the National Film Theatre.

Facility for Airborne Atmospheric Measurements (FAAM)

Elgin gas leak: FAAM aircraft saved Total and the UK economy £2.8 billion

The use of the Facility for Airborne Atmospheric Measurements (FAAM) aircraft limited the duration of the 2012 gas leak at Total's Elgin North Sea gas platform, which cost Total an estimated $130 million and the UK economy £2.8 billion in lost corporation tax receipts (0.2% of UK GDP that year). Thanks to rapid mobilisation of the aircraft, Total was able to reoccupy the platform after environmental scientists interpreted the data provided on the gas leak collected by the FAAM aircraft.

Chapter 4: Biological sciences, health and food sector



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This chapter describes the emerging themes within the biological sciences, health and food sector (BH&F). This sector spans a broad range of research and innovation disciplines and infrastructures covering all areas of biological and medical science, from plant and agricultural science, to food science, to whole organism phenotyping, to clinical science.

Advancing our understanding of living organisms from microbes to humans – their molecular and structural complexity, their interactions, adaptions and diseases, and their environments – is at the heart of this sector. The research drives innovation in agriculture and food production, our ability to promote human health and identify and treat illness enabling us to respond to some of the biggest challenges our society faces. It supports UK competitiveness in major, globally mobile and rapidly changing industry sectors such as biomanufacturing, pharmaceuticals, health technology and diagnostics, and 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. New technologies also offer data on much larger scales and over longer time periods than previously possible. At the same time, the sector's infrastructure must support the study of life in the places where life happens, whether that be farmland, hospitals, or in the population; this shapes how the infrastructure is organised.

The two Life Sciences Sector Deals shows how life-science based industries 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. The range of capabilities and expertise needed for successful commercialisation of science is broadening, often needing stronger links with informatics, emerging technologies or social sciences, or the ability to explore change in pathways or systems involving multiple technologies and evidence synthesis. Without these capabilities there is a risk that companies will leave the UK.

Within the UK, the Biotechnology and Biological Sciences Research Council (BBSRC) and Medical Research Council (MRC) provide around half of the public sector investment. There are also major contributions from DEFRA and Health Department research funding (especially the National Institute for Health Research (NIHR) in England). The NHS also offers unique opportunities for research. The UK is very well connected with European infrastructures and is a partner in eight out of thirteen biological and medical sciences research infrastructures supported by the ESFRI programme. Health research charities, such as the Wellcome Trust and Cancer Research UK, are major investors and partners in developing infrastructure (such as Health Data Research UK) and there are increasing opportunities for industry-owned infrastructure or data resources to be developed into partnerships such as the joint MRC and AstraZeneca Centre for Lead Discovery.

This forward view of the sector was developed by drawing upon a range of inputs including relevant strategies developed by BBSRC and MRC, advice from an expert group, consultation workshops and guidance from existing advisory structures within UKRI, drawing in views from academic, charity, industry, healthcare and government sectors.

4.1 Definition and scope

To reflect the characteristics of the BH&F sector, the programme-wide definition of infrastructures has been refined to include:

- E-infrastructures such as data and computing systems and communication networks
- Major high-cost research equipment
- 'Platforms' integrating and analysing evidence utilising a multi-dimensional approach
- Resources such as data sets, collections, archives and longitudinal and cohort studies

- Innovation infrastructures or distributed networks that provide environments for collaborative research, with strong user links to accelerate impact
- National centres, buildings or laboratories to address particular research opportunities, of national or international significance

4.2 Understanding the landscape

This sector includes single infrastructures operating independently, those housed within a larger entity, networks of distributed infrastructures and e-infrastructures. These may include platforms of integrated technologies, capabilities, biological or bioinformatics resources, research facilities embedded within hospitals for discovery research or for developing and evaluating interventions, nationwide population research or clinical trials infrastructure, and national capabilities focussed on specific research challenges (figure 5). They range in scale from single pieces of cutting-edge high-cost equipment such as an ultra-high field NMR for structural biology, very long-term human population cohorts, through to field- and farm-scale platforms which comprise a range of in situ state-of-the-art instrumentation in isolated catchments for continuous monitoring of system inputs and outputs. In this sector, it is more common than not for major facilities that support basic non-profit discovery science to also support industry R&D or applied research or evaluation.

Figure 5. Biological sciences, health and food sector diversity and dependencies.

4.3 Key messages and emerging themes

Through the stakeholder engagements to help develop this chapter, the following key messages have emerged for how the UK should develop its future BH&F infrastructure.

- Networking **distributed smaller-scale infrastructures to form a national capability** is a common feature (or an aspiration in new/establishing areas). Connections across multiple sites can be essential to tackle complex research questions with scale and speed; coordination around sharing methods and expertise, planned renewal cycles and procurement can all make infrastructures more productive. Examples include networks of specialist microscopy facilities, phenotyping facilities, or bioinformatics resources. In many cases these form the basis of large-scale European infrastructures such as those on the ESFRI roadmap (e.g. Euro-Bioimaging, INSTRUCT, EMPHASIS and ELIXIR).
- **Managed, multi-level provision enables efficient use of infrastructures**. For unique or limited key infrastructure, usage can be maximised by a well-managed ecosystem. For example, providing lower specification 'feeder' instruments to optimise sample preparation and refine experimental design reduces time requirements on the 'main' highly specified instrument. This approach should be routine for state-of-the-art cryo-electron microscopy or ultra-high-field NMR facilities.
- **Infrastructure in context:** medical and agricultural research and innovation always need strong underpinning facilities based in the real world, in general or specialist hospitals for example, or representative agricultural sites or population research centres close to the people volunteering. Here, it is vital that the local environment (including non-research aspects e.g. health service operational change, or biosecurity), as well as research and the need for a sustained productive partnership around the facility are fully considered in funding decisions and organisational models.
- The need for **centralised versus local** infrastructure is often dependent on the nature of the research being conducted. For example, samples which are stable e.g. 'fixed' can often be studied in a central facility, whereas research on 'live' samples (e.g. patients or in vivo animal systems) or unstable molecules (e.g. radio-isotopes) requires dispersed or localised facilities, often co-located with other necessary infrastructure (e.g. hospital settings). Further complexity is added where the samples require specialist containment (e.g. biohazards).
- Increasingly in the life sciences, new knowledge is derived by co-locating different capabilities provided by different instruments to form **integrated and automated platforms**, enabling a series of complex assays or protocols to be undertaken sequentially on the delivery of a sample. The 'lab of the future' will involve high-tech robotics and automation of routine assays. They will comprise high-cost, cutting-edge analytical infrastructure for molecular and cell biology (including e.g. imaging, 'omics, cell culture and manipulation), together with complex data networks and new bioinformatics, statistics, computing and software solutions (including machine learning) to automate and link the technologies, and to correlate data analyses across genotype, phenotype and functional measurements. The increased use of automation and robotics will increase the precision and throughput of research. High levels of automation will also affect human interactions and research culture.
- **'Big Data':** developing the infrastructure and capabilities to integrate diverse datasets will lead to **accelerated use of sophisticated modelling** and to supporting of heterogeneous multiple modelling, e.g. modelling the spread of infectious disease and zoonoses. This is closely linked with the requirement for appropriate **e-infrastructure** to manage the **integration, analysis and interpretation of data**. The 'data tsunami' arising from the shift from empirical science to data-intensive research has been acute in the life sciences, with the rise of large-scale high-throughput technologies (e.g. 'omics, imaging) which produce terabytes of data each day,

often requiring the use of **AI approaches** (such as machine- and deep-learning) to unravel this progressively data-rich environment. To enable the integration of diverse data types, there is a parallel need for standards development and adoption and consideration of data security due to the use, generation and linkage of personal biomedical/health data.

The following section and tables summarise the emerging themes from our work so far. The thematic areas are organised around areas of capability or scientific challenge. For example, a technology-led theme may be focussed on a well-established area for infrastructure investment, e.g. imaging, but looking ahead to future needs, or it may consider the capabilities or innovation that is needed to progress a scientific challenge, e.g. multi-scale, dynamic biological systems, where informatics and the integration of many types of technology are all vital for success.

These thematic areas highlight some existing infrastructures and capabilities, as well as reflecting likely future needs to 2030. Most themes overlap and interact within this sector and across other sectors. This reflects the different strands of science that use the same technology to different ends or to study different model organisms. It also reflects the dependencies and interactions across the scientific sectors.

Theme 1: Multi-scale dynamic biological systems

To provide a dynamic systems-level insight, moving beyond understanding the cell at independent scales towards multi-scale biology.

Innovative technologies and approaches will transform our understanding of biology at multiple levels, spanning systems, organs, tissues, cells, subcellular niches and structural biology and gene regulation. The goal of multi-scale analysis is to study and understand how events or changes at one scale affect all the others. The vision is to explore interactions 'in real time' and ultimately to model the interplay between cell-signalling pathways, networks, tissue and organ functions, mechanics and organism physiology. This will then need to be contextualised according to linear time, whether in relation to cell cycle, development or ageing. Ultimately, this will provide insights into how perturbations like environmental toxins or disease affect plants, animals and humans. These insights will improve the design and development of new treatments or diagnostics. It will also open new modes of research, e.g. multiscale modelling of medicinal chemistry, cell function and physiology. These new approaches will be enabled by the emergence of new methods of single cell analysis, imaging of thick tissues at high or super-resolution, multiplexed labelling of biomolecules to reveal up to 100 different pathways at once and deep proteomics. These allow researchers to visualise biology at very high resolution across multiple scales (from sub-molecular through cells to tissue) and to quantitatively analyse processes and functional readouts with extraordinary precision (e.g. through 'omics) and at scale and over time.

Over the next five to ten years, UK science will endeavour to close the gaps between structural, cell and organismal biology, and develop a co-ordinated national network that provides access to high precision technologies and supporting infrastructures. A key component of this effort will include the development and deployment of open access public data resources that will provide benchmarked datasets that the scientific community can use to develop the data analysis, modelling and integration tools that will be required to achieve this vision. This will allow UK scientists to capitalise on current research strengths in understanding the complex interplay between signalling pathways and networks, spatial organisation and local environments, and near or long-distance control systems.

The outcome of these efforts will be a systems-level understanding of biological function within cells, tissues and organisms that we have long strived for. For example, creating a full understanding of how the human immune system works, in terms of regulating responses to infection or chemotherapy, through to more systemic interactions with organ systems, or providing insights into brain homeostasis from neuron to synaptic network, as it relates to cognition, intelligence and resilience to trauma or disease.

Ensuring the UK develops both a highly skilled workforce and access to highly specified equipment and platforms will lead to revelations in how normal function is achieved and precisely how it is compromised in disease and after environmental exposures. These insights across the biological and clinical spectrum will support innovation as the technology is harnessed for new therapeutic targets and approaches.

This over-arching theme provides the vision for the following 'sub-themes' specifically addressing the infrastructure needs for:

- Biological and biomedical imaging capabilities
- Mastering the proteome and metabolome
- Future capability in structural biology

<table>
<tr><th colspan="2">Theme 1: Multi-scale dynamic biological systems</th></tr>
<tr><th>Science, research and innovation challenge</th><th>Potential capability required</th></tr>
<tr><td>Multi-scale dynamic biological systems
Develop a national infrastructure to harness and expand innovative technologies to deliver a transformation in understanding of biological systems, cells and their interactions, allowing the interplay between cell-signalling pathways, networks, spatial organisation etc. to be understood at the systems-level in health and disease. This will lead to an explosion of knowledge, targets and opportunities for innovation and translation.</td><td>Co-ordinated UK investment to create a national infrastructure including:

• Highly specialised centres of scientific excellence with access to new technologies for imaging, 'omics, cytometry, structural biology
• Analytical infrastructure with interconnected data platforms to support correlative analysis across phenotypic and functional measurements
• Skilled workforce to operate, link and correlate data
• Robotic, automated and AI approaches
• Suitable e-infrastructure

These should link to other international virtual/ distributed infrastructures such as ELIXIR.</td></tr>
</table>

Theme 2: Biological and biomedical imaging capability

Imaging is now the dominant form of analysis of molecules, cells and tissues across the life sciences. Imaging of biological samples, or bioimaging, is an area of significant importance as bioimaging technologies cut across disciplines, from plant and animal phenomics through to health diagnostics and therapeutic delivery.

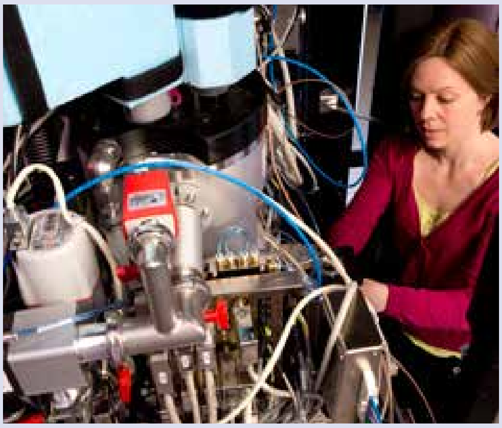
Bioimaging operates at spatial scales from nanometres to metres and time scales from microseconds to years. It employs high-voltage cryo-electron microscopes to reveal the atomic structure of biomolecules, powerful super-resolution microscopes that break the light diffraction barrier to reveal the properties and dynamics of cells and tissues, and X-ray and magnetic resonance or other forms of tomography to reveal the underlying architecture of plants, animals or humans. Super resolution imaging offers huge promise for understanding biological mechanisms in health and disease as well as clinical diagnostics, e.g. the application of bioimaging and automated machine-learning algorithms to a new generation of cancer diagnostics and to precision medicine approaches more generally.

The rapid pace of technology development in bioimaging has opened many scientific opportunities and it is now routine to measure and visualise biological molecules and dynamics that were impossible five years ago. In most cases, imaging methods provide quantitative information which must be processed and analysed to reveal detailed phenotype and functional readouts of cells, tissues and organisms. This produces terabyte-scale datasets that must be handled, processed and understood, thus challenging the informatics and computational resources of research laboratories, institutions and even national resources. The development of new data management, reduction, modelling and AI tools are an essential part of the bioimaging infrastructure. On the short-term horizon there are also potentially transformative technologies in electron tomography, pulsed electron microscopy and hyperpolarised MRI. These techniques will require an infrastructure to support new sample preparation approaches.

The UK bioimaging community fosters strong interactions with the physical and engineering sciences (particularly for technology development) and with the medical and environmental sciences, where bioimaging underpins many important applications. Strong bioimaging facilities across the UK are valued by the imaging industry as hubs of technology development, training and expertise. UK developments in bioimaging have led to notable technologies that have been commercialised and are now used worldwide, demonstrating the important contribution that UK bioimaging infrastructure and expertise can make to the bioeconomy.

Cryo-electron microscopy (cryo-EM)

Cryo-EM was developed by scientists at the MRC Laboratory of Molecular Biology and subsequent improvements to cryo-EM techniques in the 1990s by the team led to the development of better detectors for electron microscopes and better software to analyse the images of proteins. The significance of cryo-EM in revolutionising our ability to look at biologically important molecules in unprecedented detail was recognised when Dr Richard Henderson was awarded the 2017 Nobel Prize in Chemistry.



MRC Laboratory of Molecular Biology

Imaging scientists, the staff who hold and deliver expertise in running imaging systems and extracting the most out of imaging data, are a key component of UK's bioimaging infrastructure and must continue to be supported. They have formed active, collaborative networks that share expertise, deliver new approaches and help define common methods of using and accessing bioimaging technology.

The bioimaging landscape encompasses a breadth of technologies and combines widely available, workhorse technologies to absolutely cutting-edge, one-of-a-kind resources. Access for UK researchers to bioimaging resources occurs at a variety of scales: from local core facilities, through to national and international centres. Infrastructures have a variety of shared access mechanisms and a distributed network of diverse resources is essential to provide access for UK researchers to the full range of available infrastructure.

The sector needs coordinated investment at scale to maximise the opportunities for new fundamental scientific discovery, health diagnostics, precision medicine through to translation and application in industry. The integration of image data with other data types, for instance genomic and transcriptomic data, will enable further breakthroughs. To realise these ambitions investment in a combination of key capabilities, infrastructures and highly-skilled people are all essential.

Theme 2: Biological and biomedical imaging capability	
Science, research and innovation challenge	**Potential capability required**
Biological/ biomedical imaging capability Imaging is the dominant form of analysis of molecules, cells and tissues across the life sciences. Imaging of biological samples and bioimaging technologies cut across all areas of the BH&F remit and operate across all scales and dimensions.	The breadth and prevalence of imaging throughout the BH&F sector requires an 'ecosystem' of infrastructures including: • Regional advanced microscopes (e.g. Cryo-EM, PET) supported by a network of local 'feeder' microscopes and sample preparation capabilities • The development of appropriate data solutions to support the storage and manipulation of large data files and collections • Development of skilled staff to support bioimaging capabilities (technical and data) • Specialist national facilities (e.g. the Research Complex at Harwell - RCaH, RFI) • Networks (e.g. Bio- and Clinical Imaging Networks) • International facilities such as those provided by ESFRI projects (e.g. EuroBioimaging)

Theme 3: Future capability in structural biology approaches

To understand the molecular structure and dynamics of biological macromolecules (particularly proteins and nucleic acids) and how alterations in their structures affect their function.

The structural analysis of biomolecules is of fundamental significance for modern biological science. Using a variety of imaging techniques, molecules can be viewed in three dimensions to see how they are assembled, how they function, and how they interact. This has helped researchers understand how the thousands of different molecules in each of our cells work together to maintain health. Structural studies can show how misshapen molecules lead to disease, and as a result, such studies have influenced new treatments.

Structural biology can reveal detail missing from conventional microscopy which is limited either by the physical boundaries of magnification, or because the samples themselves are not physiologically active. Structural biology methods provide the technology to push beyond these limits bringing molecules to life in 3D and into sharper focus. X-ray crystallography, nuclear magnetic resonance, optical and electron microscopy, tomography and mass spectroscopy give different views of macromolecules at different scales. Bringing all of these techniques together via correlative structural biology, enables elucidation of not only the structure of a protein, but also how it functions and what it interacts with. Great strides in automation and standardisation in the 'hard' end of these technologies have transformed productivity.

The challenge is to go beyond determining the structure and biochemical properties of a protein in vitro, and to understand how proteins function dynamically and are coordinated at a cellular level or even organism level, by integrating approaches spanning different resolution scales.

Theme 3: Future capability in structural biology approaches	
Science, research and innovation challenge	**Potential capability required**
Future capability in structural biology approaches To understand the molecular structure and dynamics of biological macromolecules (particularly proteins and nucleic acids) and how alterations in their structures affect their function.	The breadth and prevalence of structural biology requires an 'ecosystem' of facilities for biomolecular and 3D structural analyses: • Regional and national infrastructures backed by integrated training programmes (in very, and ultra, highfield NMR, cryo-EM, synchrotron) supported by a network of local 'feeder' instruments and sample preparation capabilities • A renewed effort to fund interdisciplinary research in the development of structural biology instruments of the future • Specialist national facilities and networks (for example the LMB, Crick, RFI, RCaH the Central Laser Facility (CLF) and the Diamond Light Source (DLS)) • International facilities such as XFELs, synchrotrons and those provided by ESFRI projects

Theme 4: National and international biosecurity: animal and human zoonotic and vector-borne diseases, antimicrobial resistance and plant health

Enabling research to tackle zoonotic and vector-borne diseases of animals and humans, resistance to antimicrobial compounds and risks to plant health to help prevent, control and eradicate major human, animal and plant diseases, protecting human health, livestock and crops, and supporting the economy.

Animal and human zoonotic and vector-borne diseases endanger animal welfare, food security and human health and are also associated with significant risk of economic loss. The UK alone has been hit by various outbreaks of such diseases over the last two decades, including the Foot and Mouth epidemic in 2001 and the Swine Flu pandemic in 2009. The costs for these events have been estimated at around £2.5 billion of compensation for slaughtered animals and more than £1.2 billion for the influenza outbreak[45].

Additionally, the overuse and misuse of antibiotics in human health and intensive livestock farming has led to an increase in antimicrobial resistance, including resistance against colistin, the antibiotic of last resort. Whilst reports of this resistance in humans are rare but growing in numbers, the cases of colistin resistance in livestock are increasing at an alarming rate[46].

Furthermore, there are over 900 pests and pathogens that currently pose a threat to the UK's arable crops, trees, horticulture and wild plants. Taking the above into account, it is essential that the UK develops an integrated, whole-system approach to animal, human and plant health building on the Strategy for UK Plant and Animal Health Research[47].

Hence, the UK requires the capacity and capability to support research into the cause and the eradication of pathogenic plant, animal and human diseases, and the prevention of antimicrobial resistance. This includes national basic research and reference laboratories, diagnostic facilities and containment facilities for pathogens requiring BSL-3 or higher. The facilities to foster and translate technology developments, such as the development of new vector control methods, infection prevention and control approaches and vaccines are also key to retaining the UK's position as a world-leader in this space, along with building on the European and wider international partnerships that exist with other countries. Additionally, there is a real need to attract technical experts to work in infrastructures in this field to maintain UK expertise.

This thematic area has important overlaps with the thematic areas covering animal genomics, plant genetics and phenotyping, and population data for health research and innovation. Hence, there is the need to take a holistic view across these areas. This will enable us to form a clearer picture of what relevant infrastructure we have and how we might foster better coordination across these overlapping areas. This should take into account funding provided by other funding agencies, industry and government departments such as DHSC (PHE), DEFRA and associated agencies (APHA and FERA), DSTL and the WHO/FAO.

Theme 4: National and international biosecurity: animal and human zoonotic and vector-borne diseases, antimicrobial resistance and plant health	
Science, research and innovation challenge	**Potential capability required**
National and international biosecurity: animal and human zoonotic and vector-borne diseases, antimicrobial resistance and plant health • Enabling research to tackle zoonotic and vector-borne diseases of animals and humans, risks to plant health and resistance to antimicrobial compounds to help prevent, control and eradicate major plant, animal and human diseases • Includes impacts on human health, animal and plant health	• Research, surveillance, diagnostics, vector facilities and vaccine production for highly pathogenic viruses and other dangerous animal and human pathogens form a vital part of the UK's preparedness in the event of disease outbreak or other attack • Antimicrobial development facilities, to support robust new therapy pipeline • National capability comprising high-containment facilities (BSL-3 and BSL-4), including national and world reference labs (e.g. The Pirbright Institute, The Roslin Institute, DSTL, PHE, CVR, Crick Institute (including WHO Worldwide Influenza Centre), CEFAS, APHA, Pandemic Influenza Preparedness Centre, Nottingham) • Develop a UK Animal and Plant Health IoT, which will enable fast systematic detection, analysis, understanding and prediction of animal and plant health risks. Alongside/as part of this establish a national database for monitoring farmed animal diseases • Infrastructure for innovation and technology transfer

Theme 5: Food safety and nutrition

Integration of multidisciplinary bioscience and clinical knowledge to develop new understanding about the relationships between diet and health through integration of nutrition, agriculture and food processing research for the production of safe and nutritionally enhanced food and animal feed.

The food manufacturing sector in the UK is larger than the aerospace and automotive sectors combined, both in terms of GDP and employment. However, investment and infrastructure is needed to address three strategically important areas of public responsibility: food and feed production, human nutrition for health and food safety. Public sector investment is required due to:

- The complexity of the science challenges can only be addressed by fully integrating fundamental crop science, food science, nutrition, basic bioscience and clinical research
- The science supports policy guidance, strategic advice and basic information to wider government and industry stakeholders
- Significant gaps in our understanding of the relationship between food, nutrition and health
- Small profit margins in the food and drink sector and short time scales

In addition to infrastructures that enable scientific analysis of food and feed, cohort studies fulfil an essential requirement when investigating social contexts, the psychology of food choice and the effects of nutrition and the gut microbiome on health.

Theme 5: Food safety and nutrition	
Science, research and innovation challenge	**Potential capability required**
Food safety and nutrition Integration of multidisciplinary bioscience and clinical knowledge to develop new understanding about the relationships between diet and health through integration of nutrition, agriculture and food processing research for the production of safe and nutritionally adequate food and animal feed whilst sustaining food security.	• Facilities enabling the integration of biological and clinical sciences to investigate the nutritional composition and nutrient bio-accessibility of food, the effects on health including non-communicable diseases, animal production, product development, analysis, manufacturing and processing • Includes specialist institutes (Quadram Institute, Rowett Institute, Campden BRI, Leatherhead Food Research) and cohort studies for the analysis of population effects • Long-term cohort studies to study the psychology of choice and social context, and the interaction of foods with your genome, leading to personalised diets

Theme 6: Next generation plant genetics, plant pathology and phenotyping

An integrated infrastructure of equipment and capabilities for plant genetics, genomics, pathology and phenotyping is required to 'bridge the genotype to phenotype gap' to maximise yields and sustainable crop production.

This thematic area addresses the molecular basis of plant life, to maximise the health, quality and yield of plant and crop species whilst enhancing environmental resilience and sustainability to directly benefit agriculture, the environment, soil and human health. To achieve this goal it is essential to support 'genome to phenome' predictive breeding capabilities, which include a multi-faceted approach working with a range of


CropQuant

CropQuant is an infield, multi-scale crop monitoring platform designed to automate and improve phenomic data capture during plant growth. The system provides insight into key traits affecting crop yield within a working field environment, such as crop characteristics and environmental conditions, using digital sensors, sophisticated modelling techniques and a centralised server. These data enable breeders and scientists to evaluate the effect of environmental factors upon crop traits, growth and development, which could help generate higher yields and increase food security. The system can provide insight into key traits affecting crop yield within a working field environment to inform and advise breeders and scientists about the effect of environmental factors on the growth of crops, helping to provide greater yields and contributing to better food security.

technologies and harnessing multiple data types and inputs.

Germplasm development in major crops is pre-competitive; hence, the need for public sector investment to provide markers and develop phenotyping tools and technologies for breeders (e.g. the 'Designing Future Wheat' programme). Furthermore, the R&D budget for the crop breeding industry is far too limited to support germplasm development using 21st century approaches. Further benefits to agriculture and the economy can be realised by research into precision agriculture, with the goal of optimising returns on inputs while preserving resources. To deliver this, a range of equipment and capabilities will be needed to enable the necessary infrastructure to function across scales and types. This may span a range of capabilities including specialist molecular biology laboratory facilities (with appropriate containment where needed), high-throughput and specialist sequencing technologies, plant transformation facilities, controlled environment growth rooms and glasshouse facilities and field-scale trial sites. Combined with this, appropriate multi-scale phenotyping facilities are required, encompassing advances in robotics technology as well as large-scale field infrastructure and UAVs delivering 'lean' field phenotyping. E-infrastructure is also required to support integration of data outputs and associated metadata, which allows data storage, sharing, management and visualisation, as well as modelling approaches that scale from individual plants to canopies and can link to, for example, future climate models. AI will have an increasing role to play in all these aspects of crop research and will require distributed facilities for petabyte data storage and analysis.

It is also important to consider the skills and resource needs to support such a capability, highlighting the requirement for researchers and technical staff with interdisciplinary skills across plant sciences, engineering (including robotics and automation), computer science (including deep learning, AI, computer vision) and mathematics (including modelling, statistics).

Theme 6: Next generation plant genetics, plant pathology and phenotyping	
Science, research and innovation challenge	**Potential capability required**
Next generation plant genetics, plant pathology and phenotyping • Understanding the molecular basis of plant life to maximise health, quality and yields • 'Genome to phenome' predictive breeding to deduce the effects of environmental factors • Multiscale integrative approaches to quantify plant traits from cellular to organismal to field-scales	• An integrated spectrum of equipment and capabilities forming a holistic infrastructure. Centres of excellence with tailored specialist facilities (e.g. John Innes Centre, Rothamsted Research, NIAB, Hounsfield Facility at Nottingham) • Infrastructure solutions for data outputs and associated metadata across capabilities, encompassing modelling and integration • Large-scale phenotyping platforms (e.g. the National Phenomics Centre), field-scale systems (e.g. CropQuant), farm platforms (e.g. North Wyke), plus access to international facilities such as those provided by ESFRI projects (e.g. EMPHASIS) • Interdisciplinary skills across biosciences, engineering, computer science and mathematics

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

To enhance the lives and productivity of farmed animals (and humans) through research in animal biology by improving sustainability, welfare and controlling infectious diseases.

To understand the common mechanisms of animal development and pathology, knowledge from genetics, cellular, organ and systems biology must be integrated to allow us to shed new light on the highly complex workings of living organisms. The need for new approaches is recognised to meet the growing challenges of livestock production and to control infectious diseases that threaten humans and animals.

The unravelling of the genome of an increasing number of species is giving researchers and breeders new tools to meet the increasing demand for sustainable production systems with healthy animals that supply more with less input.

A major challenge is connecting genotype to phenotype, but significant progress has been made in associating sequence variation with quantitative phenotypes, motivated by the importance of animals as food sources, as well as models for human health and development. This could include applications of research supported by relevant infrastructures into the biomedical field. Genetic knowledge can also have positive influences on welfare through the selection of more social animals or those with a reduced environmental impact and address changing consumer demands, all contributing to the well-being of people and animals alike.

Theme 7: Advanced animal genomics, developmental biology and breeding infrastructures	
Science, research and innovation challenge	**Potential capability required**
Advanced animal genomics, developmental biology and breeding infrastructures To enhance the lives of farmed animals (and humans) through research in animal biology by improving sustainability, productivity and welfare and controlling infectious diseases.	• Integrated specialist facilities and centres of excellence which enable the molecular biology (including sequencing and genomics), plus facilities for genome engineering of farmed animals from livestock through to aquaculture species • Genetic diversity resources coupled with breeding facilities, animal houses and aquaculture facilities (e.g. Edinburgh Genomics, National Avian Research Facility at Roslin and CEFAS) • Infrastructure solutions for data outputs and metadata across capabilities, encompassing modelling and integration • Large-scale phenotyping platforms (e.g. LARIF, Roslin Institute), plus access to international facilities and resources such as those provided by the global FAANG consortium • Access to translation facilities for e.g. vaccine development and production and generation of breeding lines • Infrastructure focussed on gene editing/ genetic engineering of animal species including livestock for improved productivity/disease resistance and arthropod vectors to control populations of pests

Theme 8: Resolving human physiology and pathology at depth and scale

Delivering world-leading experimental medicine infrastructures to improve clinical outcomes. Investing in the UK's clinical infrastructure to analyse human phenotypes with high precision and at scale will drive unprecedented insights into the underlying biological processes in human health and disease. This will drive innovation through the translation of findings to support early disease diagnostics, new therapies and approaches to clinical care.

The UK is an international leader in clinical and population research. Major national investments at the biomedical, clinical and commercial interface include the NIHR Biomedical Research Centres[48] and Clinical Research Facilities, MRC's experimental medicine and stratified (precision) medicine initiatives and the joint MRC and Innovate UK Biomedical Catalyst. Advances in non-invasive techniques such as medical imaging, combined with powerful high-throughput 'omics technologies, now allow us to approach the human as the ultimate experimental model for improving human health.

To maintain the UK as a world leader in experimental and translational medicine will require investment in a national network of distributed technology clusters and specialist skills that are linked with the clinical setting to reveal high-precision human phenotyping at scale (i.e. sub-populations). This will build on previous investments, through the MRC's

2013 High-Throughput Science and 2015 Clinical Research Infrastructure[28] Initiatives that supported precision analytics and next generation clinical imaging. Underpinned by new data platforms and software solutions (e.g. AI), this new distributed infrastructure will support integrative approaches that bring together molecular signatures of disease with high-resolution images of organ and whole-body systems (including MRI, PET, MEG, EEG, CT). This will transform our understanding of underpinning mechanisms of pathophysiology, provide an enhanced environment for proof-of-concept research in clinical medicine and help fulfil the promise of precision medicine.

A national, long-term strategy is needed to deploy investment at scale and maximise coordination and leadership across the clusters in crucial areas of access, capacity, procurement, training, technology interfaces and replacement/renewal cycles. A national focus will also support much needed capacity building within clinical research (e.g. academic pathology and clinical pharmacology) and provide an ideal environment for new collaborative ventures between the biomedical research, health and industry sectors.

Theme 8: Resolving human physiology and pathology at depth and scale	
Science, research and innovation challenge	**Potential capability required**
Resolving human physiology/pathology at depth and across scales Grow the national infrastructure to develop the UK as a leader of in-depth studies in humans. Experimental medicine will increase innovation from UK scientific discovery and develop new early diagnostics, therapies and approaches to clinical care.	• **UK Clinical Infrastructure Network:** Co-ordinated programme to grow and develop a UK network of world leading facilities ('omics, imaging, analysis) for in-depth studies in humans • **Capacity building** to increase the number of clinical researchers in supporting areas, e.g. academic pathology and clinical pharmacology • **Integration** platforms to support access and data linkage between the technologies and integration across the academic, clinical and industry sectors • **Academic/industry/health partnerships** to improve the validation of treatment targets, which will support innovation and greater tripartite working across academic, clinical and pharmaceutical sectors

Theme 9: Population data for health research

Creating modern population cohorts embracing advances in technology and data linkage to establish world-leading longitudinal populations to allow researchers to tackle priority areas in health and disease.

The UK is internationally renowned for its population-based health research, including epidemiology, longitudinal cohorts and biobanks. Population approaches are crucial in observing natural variation and their impact is highlighted by the global effects on public health stemming from the 1950s Richard Doll study of a cohort of GPs which first identified the harmful effects of smoking. Although highly valuable, many of the UK cohorts are aged and use the methods of their time. The MRC Cohort Strategic Review[49] highlighted that few studies had whole genome sequencing or other 'omics' information. The review also highlighted important gaps in our cohorts for example there are few cohorts that capture information around the key life transition from childhood-to-adolescence-to adulthood.

The keystone to increasing the utility of population-based health research is the availability of rich, complex data from very large cohorts of people. The wealth of data provides an invaluable platform for analysis by researchers across wide disciplines (e.g. epidemiologists, social scientists, technologists and translators). For example, understanding the biological, social and environmental influences during the transition to adulthood could provide valuable insights into the maturation of the human brain as well as keys to the biomedical and social determinants of mental health. In contrast, examining large biomedical data sets (i.e. from >1 million people) will increase the detection of very early and subtle molecular markers or changes in morphology that identify precursors to disease. Having access to such a platform would allow highly precise and sophisticated phenotypic and genotypic analyses, revealing ground-breaking insights into the role of biological, environmental and lifestyle factors shaping human health and disease. The application of new approaches, e.g. machine learning, will support the identification of subtle signals within complex data. This approach will drive advances in key clinical areas around molecular and digital pathology, early detection, improved stratification of disease and potentially revolutionise therapeutic development and clinical care.

Alongside the development of new specific cohorts is the need to embrace the digital age supporting modern cohort design and larger networks with linkage to other data platforms. Seizing the opportunities to link UK research data to other data sources such as electronic health records and/or other routine administrative data forms such as Data Linkage Scotland[50] would provide additional power in understanding the complexities around health and disease. A new administrative hub is required to support appropriate curation of cohort studies across the bio/health/social space which follows the FAIR principles to be findable, accessible, interoperable and reusable.

As cohorts are by necessity a long-term investment, many are supported by a coalition of funding agencies. In addition to UKRI for support cohorts, this includes public funders (DHSC, Scottish Government) and charities (e.g. BHF, CRUK and Wellcome). Going forwards, there will be greater opportunities to engage with industrial partners to take forward biomedical/clinical studies to support translation of discovery research into the development of new diagnostics or treatments, not least because the coalescence of UK expertise with the ability to provide rich phenotyping and link to the NHS offers a unique global capability.

The roadmap provides an opportunity to create new, valuable and ambitious cohorts within the UK, positioning us as the international leader in delivering population data for health research.

UK Biobank

UK Biobank is a major national and international health resource aimed at improving the prevention, diagnosis and treatment of serious and life-threatening illnesses – including cancer, heart diseases, stroke, diabetes, arthritis, osteoporosis, eye disorders, depression and forms of dementia. It follows the health and well-being of 500,000 UK volunteer participants and provides anonymous health information to approved researchers in the UK and overseas, from academia and industry. This is developing a powerful resource to help scientists understand why some people develop particular diseases and others do not.

Theme 9: Population data for health research	
Science, research and innovation challenge	**Potential capability required**
Population data for health research Creating modern population cohorts embracing advances in technology and data linkage to establish world-leading highly phenotyped and frequently sampled longitudinal populations that will allow researchers to tackle priority areas in health and disease.	• **Strategy for population data** to support the development of UKRI strategy for social and health data, e.g. a new administrative hub to consider approaches to long-term curation • **New health data cohorts:** establishment of new, well-phenotyped cohorts to support UK priority areas (e.g. the transition to adulthood and early detection of disease) which take advantage of modern design, linkage and 'omics approaches • **Develop academic/industry/health partnerships** to enable the use of population data for health research to deliver translation and innovation partnerships for public benefit

Theme 10: Synthetic biology and industrial biotechnology

Synthetic biology is the design and engineering of biologically based parts, novel devices and systems, as well as the redesign of existing, natural biological systems. It has the potential to deliver important new applications and improve existing industrial processes, including through industrial biotechnology, which uses cell factories and enzymes for producing and processing materials and chemicals for food and non-food applications.

Synthetic biology draws on principles elucidated from biology and engineering and has the potential to provide important new applications and improve existing industrial processes. It was named as one of the 'Eight Great Technologies' by the UK government in 2013[51], consolidating and further advancing the UK's position amongst global leaders in the field. It is also an area that has been recognised internationally as a priority area for focussed development efforts[52].

Modern industrial biotechnology is strongly supported by synthetic biology through the provision of tools and technologies such as metabolic engineering, seamless genome modification, chemoenzymatic synthesis and enzyme repurposing (Frances Arnold, Nobel Prize 2018). Industrial biotechnology through synthetic biology is beginning to address challenges and areas of research that have until recently been unattainable.

The tools and technologies developed through synthetic biology and the products and processes enabled by industrial biotechnology will have significant impact on the pharmaceutical, biopharmaceutical, medical, agricultural, bioenergy, ecological, chemical and material science sectors. It thus has a key role in establishing important new products and is essential in establishing a sustainable bioeconomy, moving away from the fossil fuel-based economy.

To deliver against these aspirations, the UK needs to have the capacity and capability to support research and innovation in synthetic biology and industrial biotechnology at all technology readiness levels to benefit from the opportunities offered in this area. This requires state-of-the-art integrated laboratory facilities offering high-throughput approaches to development, prototyping and analytics, through to pilot-scale facilities and production-scale testing capabilities, with appropriate linkages to end-users/early adopters whether in the agritech, engineering or biomedical sectors. Additionally, the ability to apply advanced chemometrics and other digital techniques to the data generated to maximise the learning gained will be important.

Critical for the successful development and uptake of synthetic biology and industrial biology applications is the proper consideration of the ethical, legal and social aspects (ELSA) at all stages of research and innovation. This includes the principles of responsible research and innovation (RRI)[53] as well as consideration of the legal and regulatory frameworks at a national and international level.

Theme 10: Synthetic biology and industrial biotechnology	
Science, research and innovation challenge	**Potential capability required**
Synthetic biology and industrial biotechnology Synthetic biology is the design and engineering of biologically based parts, novel devices and systems, as well as the redesign of existing, natural biological systems. It has the potential to deliver important new applications and improve or scale-up existing industrial processes, including through industrial biotechnology, which uses cell factories and enzymes for producing and processing materials and chemicals for broad applications from agriculture to pharmaceuticals.	• Specialist centres/facilities for discovery science, comprising state-of-the-art integrated facilities including automated pipelines and high-throughput workflows (e.g. Synthetic Biology Research Centres, LMB, DNA Foundries) • Flagship centres that integrate chemical technologies into biology • Data infrastructures for advanced modelling and simulation, plus AI approaches for rational design and data analysis • Translation, application and scale-up facilities (e.g. IKC SynbiCITE, Centre for Process Innovation (Darlington, Wilton), Cell and Gene Therapy Catapult, Medicines Discovery Catapult, Medicines Manufacturing Innovation Centre) • International facilities and networks such as those provided by ESFRI projects, e.g. IBISBA • This all needs to be underpinned by ongoing work to ensure that responsible research and innovation is properly considered at all stages

Theme 11: Innovation infrastructure

Deliver a 'step-change' in impact through the creation of 'challenge orientated' or 'capability oriented' science-based infrastructure to address national demands, such as food security, clean growth and unmet areas of major health need.

The facilities needed for discovery science can provide important platforms for areas of commercialisation and industry partnership. However, in some areas additional investment is needed in facilities more focussed on industry and academic-industry collaborations. Three broad types of innovation infrastructure are already supported:

- **Accelerators** focussed around an emerging multidisciplinary opportunity or challenge, these centres of excellence bring together convergent capabilities that no single company could easily assemble. Investment potentially includes core, multi-user platforms such as SynbiCITE (the synthetic biology accelerator), relevant biological or data resources, projects addressing key gaps that hold back the development of new products, facilities for trialling new products and support staff and expertise. This model has been valuable in areas such as advanced therapeutics and other health technologies.

- **Campuses:** co-location of state-of-the-art technologies, incubator space and support staff with expertise in research, regulatory and business development areas, support growth of clusters of businesses. For example, the Easter Bush Campus, Edinburgh, focuses on animal health which efficiently leverages long-term investment in basic research on the same site.
- **Distributed partnerships** offering industry coordinated access to larger scale research and evaluation such as the NIHR Translation Research Collaborations. These focus on a disease theme and link clinical research centres of excellence with similar interests and complementary expertise. They enable larger scale, higher quality studies with progressive investment in methods and technologies.

New capability available to the life science industries will be increasingly important to deliver the Life Sciences Industrial Strategy[54]. This is due to the higher costs of accessing state-of-the-art technologies (e.g. structural biology for product development in agriculture or medicine), new challenges needing multidisciplinary technology and research approaches and the increased emphasis on quickly moving beyond bench research to R&D in real-world settings (e.g. early validation with patient data to speed up development cycles).

Theme 11: Innovation infrastructure	
Science, research and innovation challenge	**Potential capability required**
Innovation campuses and accelerators Deliver a ‘step-change’ in research, innovation and translational activities through the creation of ‘challenge orientated’ accelerators and campuses to provide long-term support and access to technology platforms and industry expertise to drive forward areas of need, e.g. unmet health needs or food security.	**Develop a strong infrastructure to:** • Support discovery science in creating greater public benefit • Drive new technologies to shift up or retain the UK’s place in the value chain of BH&F activity • Strengthen the quality and scale of infrastructure and skilled workforce (industry/clinical/academic) to support innovation and translation • Broaden the geographical base of the UK’s research and innovation infrastructure to help drive regional growth **Challenge orientated:** build infrastructure around areas of biological science, food or health need, scientific strength, commercial opportunity and/or regional strength **‘Centres’ style investment:** Develop a strong research, innovation or translation ethos, backed by training and built on combining excellent mechanistic science linked to platform-based translation. Local expertise, providing financial and technical support. Strong links and engagement with key stakeholders

Support for innovation campuses, partnerships and accelerators is essential to ensure the UK increases its reputation for developing the outputs of its world-class bioscience and biomedical research into innovative products and technologies that provide both a benefit to the UK public and an economic return to the UK.

4.4 E-infrastructure and data

Establishing a UK e-infrastructure ecosystem that enables leading-edge and transformational research and innovation.

The reliance on e-infrastructure, informatics and computation is growing significantly across the BH&F sector as it becomes increasingly data-rich, driving the need for more platforms to integrate, analyse and share complex data sets. A range of e-infrastructure solutions will be required to harness the diverse and vast sources of heterogeneous biological (molecular, pathway, cellular, systems), clinical, population and environmental research and routine data. In addition to the high-capability national e-infrastructures such as HPC (e.g. ARCHER) and cloud provision for next-generation coding and analytics, the life sciences also require ‘challenge-focussed’ infrastructures which may be nationally networked or distributed to support different disciplines, e.g. ELIXIR, Health Data Research-UK, the Earlham Institute and the Dementias Platform UK. These provide ease of access to a diverse range of validated life-science datasets supported by interoperable systems and advanced analysis tools.

Tiered infrastructure solutions are needed for biological and medical data archives and knowledge bases to hold data locally, in data centres, or in cloud-based solutions. There is also the need to align or link different data, e.g. personal and/or health data, which has particular requirements around controlled access and security/encryption. The ability to retain data for reuse over long periods of time (e.g. for longitudinal cohorts) also needs to be accommodated.

Following the FAIR principles 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 datasets for the global scientific community. However, the rate of data generation across all modalities is increasing and new data types, for example in biological and biomedical imaging, now present significant, strategic opportunities for data re-use in deep learning and other AI applications. This key, strategic opportunity to build on UK’s established position as a resource for scientific data requires additional infrastructure and skilled people to agree and ensure the adoption of discipline specific, community generated standards. All e-infrastructure solutions will need to determine approaches to retaining high-value data for long periods of time (potentially decades) in the face of rapid technology advancement (e.g. quantum computing) and the relatively short equipment life-cycle.

Chapter 5: Physical sciences and engineering sector

CERN

This chapter describes the emerging themes within the physical sciences and engineering sector (PS&E) sector. In addition to research and innovation within the physical science and engineering disciplines, this sector encompasses the important role played by national and international facilities that support interdisciplinary activity and fundamental knowledge creation across the landscape.

Knowledge generation through to application, innovation and commercialisation in this sector directly supports delivery of many of the Industrial Strategy sector deals[55], including automotive, AI, construction, nuclear and creative industries. Research and innovation within physical sciences and engineering provide solutions and technologies within the food sector, life sciences, cultural heritage, earth sciences and beyond.

Advances in technology are vital to pushing the boundaries of capability within the PS&E sector. They enable us to address the pressing scientific questions of our time that need ever more advanced capabilities from our infrastructures. Often technologies cannot be cost-effectively and reliably procured on the open market and therefore are developed in-house by skilled laboratory staff and academics. With the UK community playing a key role in building novel technology for UK and international infrastructures, we gain a significant competitive edge when participating in the highest priority international ventures.

Within UKRI, three councils (STFC, EPSRC and Innovate UK) support the majority of research and innovation activity in the PS&E sector. Other critical organisations in this sector include the UKSA, NPL and several government departments and agencies including the DSTL. International collaborations and funding are particularly important in fundamental physics where the scale of activity requires substantial investment from many partners.

To develop the emerging themes in this chapter we have drawn upon a range of inputs including the landscape surveys, a number of published and developing strategies[56,57,58,59,60,61], consultation workshops and guidance from existing advisory structures within UKRI. This work has been led by STFC and EPSRC. STFC is currently reviewing its scientific programmes including particle physics, astronomy, nuclear physics and e-infrastructure. The strategic infrastructure needs from this work will be factored into the final roadmap. We will also continue to work with the UKSA to ensure that all relevant future UK space requirements are incorporated into this report.

5.1 Definitions and scope

This sector covers all branches of physics, chemistry and mathematics and includes materials, information and computing technology, quantum technologies, healthcare technologies, digital economy, engineering and manufacturing. It does not consider the energy research and innovation landscape which is discussed in chapter 8. STFC supported large-scale facilities (national and international) are included within this sector, although many support multidisciplinary research relevant to multiple sectors.

5.2 Understanding the landscape

Research and innovation infrastructures within the PS&E landscape have a range of lifespans from a few years to decades but all need to respond to changing needs, continually refresh their capability to address new areas of science, as well as maintaining effective capability within existing science areas. This matrix of new, expanding, upgrading and retiring infrastructures ensures capability is continually evolving and maintained at the cutting edge.
The initial analysis describes how PS&E infrastructures can be characterised as individual infrastructures or small, functional sub-sectors that can be grouped together as distinctive categories (capability and discovery driven infrastructures, application driven infrastructures and challenge driven infrastructures).

The interconnectivity between infrastructures is particularly important, for example between lab-based, distributed facilities and large-scale campus-based facilities. As the scale of need stretches beyond the ability of individual organisations to finance, procure and provide the necessary support infrastructures there has been a move towards a distributed network model for facilities such as the EPSRC NRFs. These support strategic resources of national importance to provide leading edge capabilities and technique development at a national level.[62] An example of this model is SuperSTEM, the NRFs for Advanced Electron Microscopy originally solely based at the Daresbury Science and Innovation Campus. As the needs of the research and innovation community have developed, additional expertise and capability from six other institutions has been brought in to create a distributed consortium that offers access to a much broader suite of instruments and expertise than is possible within any single institution. The critical mass of expertise on the campus also forms part of the wider innovation infrastructure including provision of business incubation facilities (see chapter 3).

At the larger scale, we operate world-class, large-scale research facilities that are characterised by their long-term and technically complex nature which takes decades of planning and investment. These types of activities can only be delivered by national and international scale collaborative efforts and the UK operates three such world-leading, national facilities: the DLS; the CLF and the ISIS neutron and muon source. The UK is also a partner in two overseas facilities: the ESRF and the ILL. These facilities allow researchers to understand the structure of materials from the atomic to cellular scale. Larger scale national capabilities, such as DLS, CLF and ISIS enable research and innovation across the disciplines and because of their complementarity, specialisms and underpinning nature are co-located on the Harwell campus in Oxfordshire.

Large-scale international facilities, which include infrastructures that address astronomy, particle physics and nuclear physics, must reach consensus on strategy and priority across their respective member countries. They are less common due to their cost, but the totality of their investment is a very significant aspect of the infrastructure landscape for this sector (e.g. the Large Hadron Collider (LHC) at the CERN and European XFEL). Within the PS&E sector, campuses are a common approach to bring together an ecosystem of infrastructures to deliver complex capabilities (see chapter 3). Campuses often include small and medium infrastructures co-located with large, often national, infrastructures and innovation facilities. The Daresbury campus clearly expresses these traits, with the co-location of high-tech companies within a research and innovation campus.

Sci-Tech Daresbury Campus

Sci-Tech Daresbury national science and innovation campus was established in 2006. It supports high-tech companies to accelerate the growth of their business through innovation, collaboration and access to world-class technology facilities and business support. A joint venture between STFC, Halton Borough Council and developers Langtree, Sci-Tech Daresbury enables even the smallest start-ups to work side-by-side with successful and influential international companies. The site is currently home to over 130 science and high-tech businesses. It also hosts the Accelerator Science and Technology Centre (ASTeC) and the Cockcroft Institute that are at the leading edge of particle accelerator research, development and application; the Hartree Centre: a world-class centre of excellence in HPC, which works in collaboration with IBM Research; the European Space Agency Business Incubation Centre UK and SuperSTEM: an EPSRC national facility that houses some of the world’s highest resolution microscopes.

5.3 Key messages and emerging themes

Many critical drivers for change have been described in chapter 2 along with issues and opportunities for infrastructures in chapter 3. For the PS&E sector, other key messages identified by our community include:

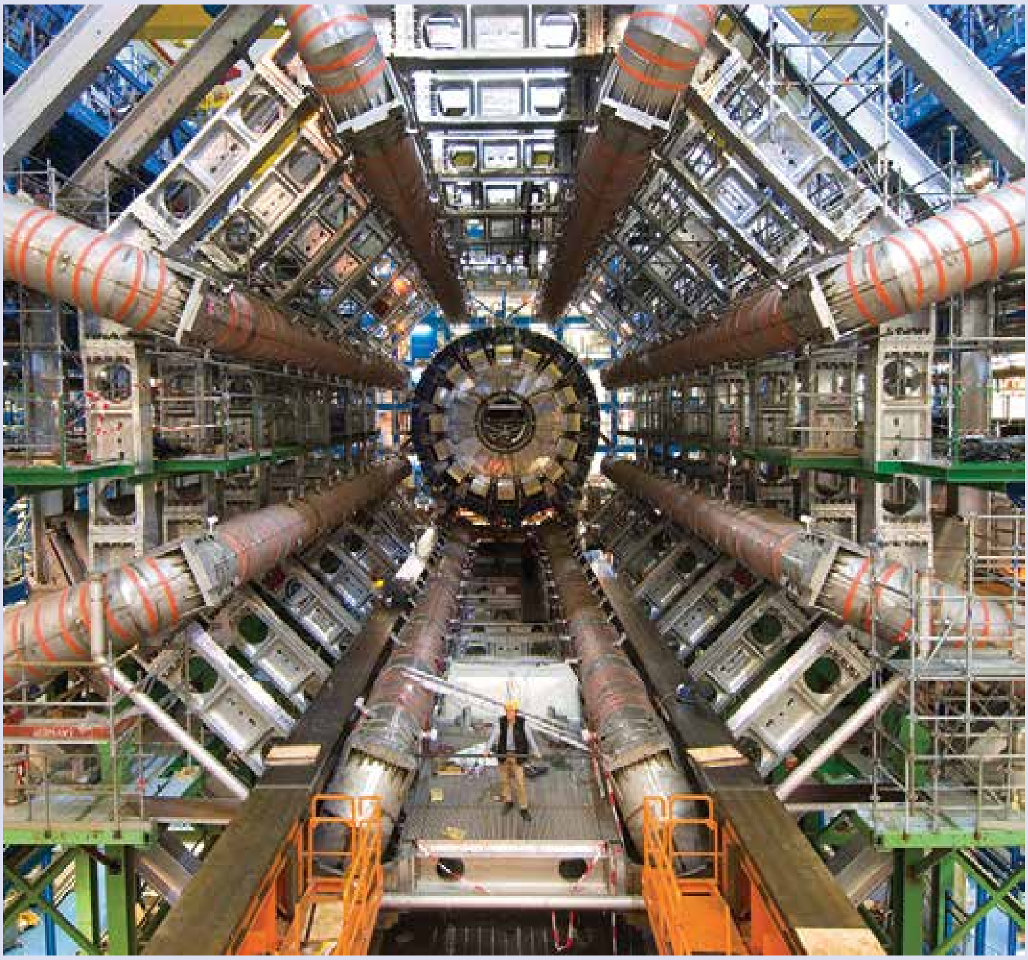
- **Continuous technical advancements** are required across a number of specific PS&E infrastructures to improve how we undertake research due to increasing complexity of infrastructures, extremely large data rates, challenging/extreme environments and the need for scientists and engineers to work together to deliver complete systems. Improvements, such as automation within sample preparation areas, could significantly improve the efficiency of processing samples, allowing greater throughput and therefore improved access to the community at these infrastructures.
- **New materials** (including nanomaterials), electronics design, systems engineering and data chains are also vital technological components that will have significant impacts on the way we carry out research. The ability to increase the scale of our research is also considered an important next step, as well as being able to study materials and matter in their dynamic state.
- **Quantum technologies** including computing, modelling, remote/cloud technology and information security are considered to be strong drivers in the PS&E sector. For example, the need for advancing quantum detectors, driven by space science but with far wider applications will progress how we do a huge variety of science and potentially have wider impacts to meet industrial needs. Quantum computing based on materials approaches is also predicted to create radically new concepts for information processing (e.g. neuromorphic computing).
- Developing a **national network of facilities** would ensure that the best and most efficient use is made of mid-range to large-scale investments through linking them with underpinning lab-based capabilities and expertise such as large STFC facilities, across a wide range of research areas. EPSRC's National Research Facilities (NRFs)[62] are providing access to a wide range of state-of-the-art equipment, specialist analysis and training to academic and industrial users. A good example of how NRFs help to bridge the gap to the large facilities is the work of the UK National Crystallography Service alongside the Diamond Light Source's small molecule single crystal diffraction beamline[62,63].
- Our engagement work with the research and innovation community so far reinforces the need for **continuous upgrade programmes at the large facilities** to ensure the UK maintains its competitiveness. The strength of UK capability also makes it an attractive base for future international facilities in the PS&E sector attracting international expertise and investment to the UK.

Based on the research and engagement to date seven of **emerging themes** and associated technical and research challenges that require multidisciplinary and international approaches to solve them have been identified. These are summarised in the following tables. For each of the emerging themes we have highlighted below a limited range of examples of the sort of research and technical challenges (the future possible ideas) that would help to deliver them. These are not intended to be examples of specific projects or infrastructure investment opportunities but highlight areas of significant challenge, which cannot be overcome without significant investments. Many of these challenges are cross-cutting themes common to more than one sector. There are also emerging themes identified in other sector chapters that have a strong overlap with the PS&E sector and there are other areas, such as, robotics, advanced fabrication, advanced materials, communications and circular economy, which could be developed further for the final landscape report.

Theme 1: Advancing knowledge

Research in particle physics, astronomy, space science and nuclear physics seeks to understand the Universe from the largest astronomical scales to the fundamental building blocks of matter. Scientists in these fields aim to answer fundamental questions including: 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?; What are the basic constituents of matter and how do they interact?

Theme 1: Advancing knowledge	
Science, research and innovation challenge	**Potential capability required**
Next generation detectors and telescopes Advancing knowledge in frontier physics will require UK participation in research and development to design, construct and eventually exploit new experiments, as well as upgrades to existing experiments. The significant scale of the research infrastructures needed for such experiments will involve long-term planning and commitments by international collaborations. The technological challenges to be overcome will present opportunities for collaborations between the research sector and UK industry, and potentially wider economic impact in sectors such as advanced manufacturing and healthcare.	**UK participation in flagship, international projects, such as:** • A third-generation gravitational wave (GW) observatory sensitive to GW frequencies as low as ~1Hz • Construction of the largest ever radio telescope with signal collecting area in excess of one million square metres • Completion, exploitation and further development of the world's largest optical telescope • Upgrades to particle accelerators and R&D towards the next generation of colliders • Next generation dark matter detectors • Participation in the next generation of space-based astronomy missions through international collaborations such as ESA **UK capability to enable:** • The ability to study matter under extreme conditions • Next generation nuclear science capability to advance studies in higher luminosities enabling our understanding of nuclear environments • Development of technologies including precision engineering, sensors, cryogenics, optics, robotics and accelerators • Computing infrastructure and skills to address big data and machine learning challenges
Theoretical physics As the experiments become more powerful and sensitive, the demands placed on the requirements for modelling, simulations and calculations to predict, test and interpret the data from the experiments will also increase.	• HPC able to meet the increased demands in data volumes and with the capability to solve different types of problems
Links to: Capability driven infrastructure	



CERN

High Luminosity LHC

The High Luminosity LHC at CERN will test the validity of the ‘Standard Model’ (the theoretical model of particles and forces) by providing more accurate measurements of known particles and will search for new particles that could address outstanding questions in particle physics, such as the nature of dark matter and the matter-antimatter asymmetry in the Universe. This upgrade of the LHC will increase the volume of data analysed by the ATLAS and CMS experiments by a factor of 10. Following five years of design study and research and development, this challenging project now requires ten years of development, prototyping, testing and implementation. Operation is expected before the end of the next decade.

Theme 2: Novel technologies for the next generation infrastructures

Advances in technology can lead to significant improvements in the capabilities of our science and engineering facilities. Equally, advances in science questions and new research directions drive forward increasingly advanced technologies. Advances in detectors, instrumentation, accelerator science, specialist engineering and optics, to list a few examples, are therefore required to maintain and build new world-leading infrastructures. 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.

Theme 2: Novel technologies for the next generation infrastructures	
Science, research and innovation challenge	**Potential capability required**
Revolutionising sample preparation Across a range of different facilities and techniques current methods for producing samples are labour intensive, require highly skilled effort and different stages of the process are often not well integrated, limiting the ability to feed-forward information and automation.	Improvements in automated sample preparation, in situ and in operando investigations and correlative imaging could have a big impact across a number of techniques

Advanced characterisation and imaging
Developing the next generation characterisation and imaging technologies will be inherently interdisciplinary and support academics and industry in areas such as health, aerospace composites, nuclear materials and semiconductor devices. They will help to understand materials at different length scales, from atoms to components.
	• Advanced imaging facilities could include:
	  • Development of an MRI scanner operating at a magnetic field above 10T
	  • A mid-range facility in X-ray computed tomography
	• Building on the recent £20 million cross-disciplinary investment in very- and ultra-high field NMR we will seek to procure the most powerful spectrometer currently commercially available, with field strengths of up to 1.2GHz, enabling:
	  • Study of the human genome and atomic structure through improved resolution and sensitivity
	  • Improved understanding of biological function
	  • Analysis of antibody proteins
	  • Study of new materials with lower concentration or sensitivity, with applications in catalysis, battery development and drug delivery

Theme 2 cont.	
Science, research and innovation challenge	**Potential capability required**
Detectors Detectors/sensors, and the supporting instrumentation, are key elements for a broad range of science areas. Improving detector technology allows us to push the limits of sensitivity, resolution and fast response to particles and electromagnetic radiation.	Detector development requires advanced capabilities in materials science, high-speed electronics, precision engineering and cryogenics often using bespoke specialised facilities and in collaboration with industrial partners.
New science facilities including free-electron lasers (FELs) and future high-energy physics particle colliders require a step change in the performance of current detector systems which needs new capabilities in the UK • Novel quantum detector technologies can have application in both space science and terrestrial facilities investigating dark matter and gravitational waves Superconducting detector technologies can enable much higher sensitivity astronomical detectors for frequencies ranging from the far-infrared to X-rays	

Bridging the gap to the large facilities
Facilitating the links between large facilities and local capability could result in greater scientific productivity and new areas of scientific discovery. In some areas, the ability to do precursor studies, analyses and sample preparation prior to accessing the large facilities would be beneficial.
	• Development of laboratory based:
	  • Ultrafast dynamic imaging
	  • Accelerator driven, low-energy light source.

Links to: Capability driven infrastructure; application driven infrastructure	

Theme 3: Next generation large-scale infrastructures

Supporting the next generation of large-scale infrastructures such as light-sources, free electron lasers (FELs), neutron sources and intense laser sources is an important element of the PS&E sector. New capabilities will help us find the solutions our country, society and world needs for the future, such as new sources of energy, addressing novel security threats, dealing with climate change and an ageing population, while at the same time building an effective knowledge-based economy.

<table>
<tr><th colspan="2">Theme 3: Next generation large-scale infrastructures</th></tr>
<tr><th>Science, research and innovation challenge</th><th>Potential capability required</th></tr>
<tr><td>Advanced characterisation and imaging
Developing the next generation characterisation and imaging technologies will be inherently interdisciplinary and support academics and industry in areas such as health, aerospace composites, nuclear materials and semiconductor devices. They will help to understand materials at different length scales, from atoms to components.</td><td>• Advanced characterisation facilities capable of:
o Imaging at the atomic scale under in-situ conditions
o Operating across all different phases – solid, liquid and gas – at the level of individual atoms
• Next generation capabilities that offer the ability to study virus structures and vaccines at the whole sample scale, or as thick samples – capabilities not currently available. Improved spatial resolution and throughput will enable access to a wider community</td></tr>
<tr><td>FELs
With their characteristics of ultrashort pulses and ultrahigh brilliance, FELs are already able to:
• Map the atomic details of viruses and cells and film chemical reactions
• Study matter under extreme conditions of temperature and pressure such as those occurring in the interior of planets, thus, revealing the properties of materials under such conditions
• Examine membrane proteins to understand their role in cancers</td><td>Access to FELs to enable a wide range of science challenges in the life, material and physical sciences.</td></tr>
<tr><td colspan="2">Links to: Capability driven infrastructure; application driven infrastructure</td></tr>
</table>

National Satellite Test Facility (NSTF) at RAL

The UK identified the need for a comprehensive set of satellite test capabilities in the UK. The NSTF, funded through the Industrial Strategy Challenge Fund, will address this need. Currently under construction, the facility seeks to provide co-located facilities for the assembly, integration and testing of space payloads and satellites. This will enable UK companies to develop next generation launch technologies and testing capabilities, construct satellites and deliver payloads into orbit. It will enable UK industry to bid competitively for more national and international contracts and ensure the UK remains a world-leader in space technologies. The facility will be operational by 2021.

Theme 4: Industrial digitisation (digital manufacturing)

The government's recent 'Made Smarter' review[64] 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, healthcare, transport, extreme environments and manufacturing and construction will produce economic impact through increased productivity and societal impact through greater use of robotics in healthcare.

Digital, autonomous and intelligent technologies are transforming manufacturing. The ability to utilise digital design alongside digital manufacturing processes to transform future industrial production and productivity could lead to a revolution in the way we work, design, produce and operate products or monitor human health through live engineering centred interaction with entities throughout their lifecycle.
This theme brings together a range of research areas including: human-computer interaction, AI and machine learning, IoT, visualisation technologies, data science, software engineering, manufacturing technologies (such as additive manufacturing), robotics, human factors operational research, cyber security, cyber-physical systems and engineering design.

Theme 4: Industrial digitisation (digital manufacturing)	
Science, research and innovation challenge	**Potential capability required**
Digital manufacturing The concept of 'twinning' – the integration and synchronisation of digital and physical objects – has emerged as a key tenet of Industry 4.0 **Powering future digital technologies** As technology and power use continues to grow (autonomous cars, computing, mobile devices), more energy efficient ways of designing, controlling and powering a diverse range of technologies are needed	• Building on existing work in the field of digital manufacturing, such as recent EPSRC investments[65] and the UKRPIF funded Factory 2050[66] • Investment in digital twinning 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 (Also see chapter 8 (Energy) Theme 1) • Whilst incorporating improved understanding of energy demand management into current technology development will have a significant impact, transformative approaches involving research in materials, power storage, electronics design, networks, control and programming will be required to reliably power the next generations of digital technologies. This will in turn enable future innovation across a broad range of sectors from healthcare, to the automotive sector, to the personal device sector and all applications of IoT technologies
Links to: Application driven infrastructure; capability driven infrastructure	

Theme 5: Future mobility

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 also a drive for electrification for aerospace in response to a combination of fuel costs and environmental targets, including European Flightpath targets and International Civil Aviation Organisation standards. Research and innovation infrastructure has an important role in addressing the Future of Mobility Grand Challenge.

Theme 5: Future mobility	
Science, research and innovation challenge	**Potential capability required**
To address mounting economic and environmental pressures, identifying new, sustainable ways of moving people and goods are needed. Decarbonised transport and automation will be at the heart of this revolution. The UK is Europe's leading aerospace manufacturing nation and second only to the USA[67]. There is significant and rapid development of aero technology (e.g. hybrid) and increasing competition from existing and emerging economies. The UK has the opportunity to become world leading in the shift to electric and autonomous flight. Developing truly sustainable, responsible and carbon-neutral travel through electrification, based on new materials, novel technologies and seamless systems integration. Detection of stresses in manufactured materials causing distortion can limit performance. Building on recent revolutions in techniques for measuring deformation, strain, stress and damage state will enable further advances in materials, key to mobility and cleaner systems, through improved design, optimisation of manufacture, extended lifetime, enhanced safety and reduced costs of man-made structures and materials.	• Creating an aviation transport system infrastructure that demonstrates the requirements, technologies and infrastructure required for hybrid, electric and autonomous aircraft • Build on existing R&D investments in propulsion and aerostructures to develop megawatt scale machines and power systems and large national-scale facilities • Test beds and demonstrators for electric vehicles (including aerospace) • Material devices labs to develop prototypes and perform material characterisation • Capability to build small scale-up devices that can be tested fully • Hybrid and electrified propulsion research facility • Neutron capability and state-of-the-art equipment for measuring full-field displacement, strain, stress and damage in complex engineering components, from micron-to metre-length scales
Links to: Application driven infrastructure; challenge driven infrastructure; capability driven infrastructure	

Theme 6: Realising quantum technologies

Quantum technologies offer capabilities that are impossible otherwise, such as seeing round corners, long-term secure communications and the prospect of solving problems that conventional computers would take the lifetime of the Universe to solve. The UK has established a world-leading position in quantum technologies research. We need to extend and take advantage of this to remain the first choice location to research, innovate and commercialise in quantum technologies. Second generation quantum technologies take advantage of phenomena such as entanglement and superposition to give capabilities that go beyond what alternative technologies can offer. This is a new pervasive technology area that will have an impact across a wide range of sectors. There are four main areas: imaging, sensing and timing, communications, and computing and simulation.

Theme 6: Realising quantum technologies	
Science, research and innovation challenge	**Potential capability required**
Development of a quantum technologies eco-system to enable the full supply chain for the construction of commercial, large-scale practical quantum computers is a significant challenge. Current quantum computers are too small to solve anything more than proof-of-principle problems that are possible to solve on current classical computers. However, quantum computers are on the cusp of coming of age and within the next one to two years international research teams, notably at Google and IBM, expect to demonstrate hardware which for the first time can outperform the best classical computers at certain special tasks. We are increasingly reliant on GPS and other global navigation satellite systems (GNSS), which are vulnerable to failure and disruption. A new generation of quantum clocks can be built into terrestrial systems as a timing backup, to provide resilience against the unavailability or loss of GNSS.	• A national quantum computing centre to address the challenges of scaling and development of software and algorithms that can exploit the power promised by these machines • A facility for manufacturing quantum computing sub-systems – including micro-fabrication, demonstrator prototyping, packaging and electronics engineering • Timing infrastructure not reliant on GPS • Quantum technologies are underpinned by novel materials that host exotic electronic states. The ability to research condensed matter is key to understanding the atomic-level behaviour of materials to enable materials of the future. This can be achieved through advancement of instruments within current facilities
Links to: Application driven infrastructure; challenge driven infrastructure	

Realising quantum technologies

In 2013, the UK government announced a £270 million investment into a National Quantum Technologies Programme. This programme seeks to accelerate the translation of quantum technologies into the marketplace, boost British business and make a real difference to our everyday lives. In the five years since 2013, the programme has grown further to become an integrated activity between the four university technology hubs of Birmingham, Glasgow, Oxford and York, a total of seventeen universities, 132 companies and government organisations, particularly the NPL, DSTL and NCSC.

Theme 7: Unlocking therapies for the future

The world continues to face disease epidemics and ongoing public health issues that require new approaches to treatment and prevention. This will need innovation in drug delivery, discovery and targeting; personalised manufacturing for health; insight from advanced materials chemical biology, biological chemistry and digital chemistry; new biomarkers and monitoring systems (sensors, diagnostics); novel imaging technologies; in vitro/in silico screening approaches; biomaterials and tissue engineering and microsystems. The PS&E sector is an important contributor to developing new techniques and technologies for healthcare.

Theme 7: Unlocking therapies for the future	
Science, research and innovation challenge	**Potential capability required**
Robotic healthcare in the home Deliver world-class healthcare through exploiting advanced robotics in the home.	This might include: • Capability to develop fully automated assistive technologies and adapting to complex and changing needs, including dementia care • Personalised healthcare, including robotic caring, monitoring, diagnosis and home treatment • In-home surgery and recuperation
Digital chemistry Access to novel biologically active molecules that could treat disease continues to be a major bottleneck in the drug discovery and development process and ultimately costs thousands of lives and millions of pounds per year. The robotically driven synthesis of complex molecules promises to revolutionise access to medicine, molecular discovery and fine chemical manufacturing.	• Capability to develop and test robotically driven synthesis of complex molecules. Using these new systems to drive the chemical synthesis of target molecules.
Links to: Application driven infrastructure; capability driven infrastructure	

5.4 E-infrastructure and data

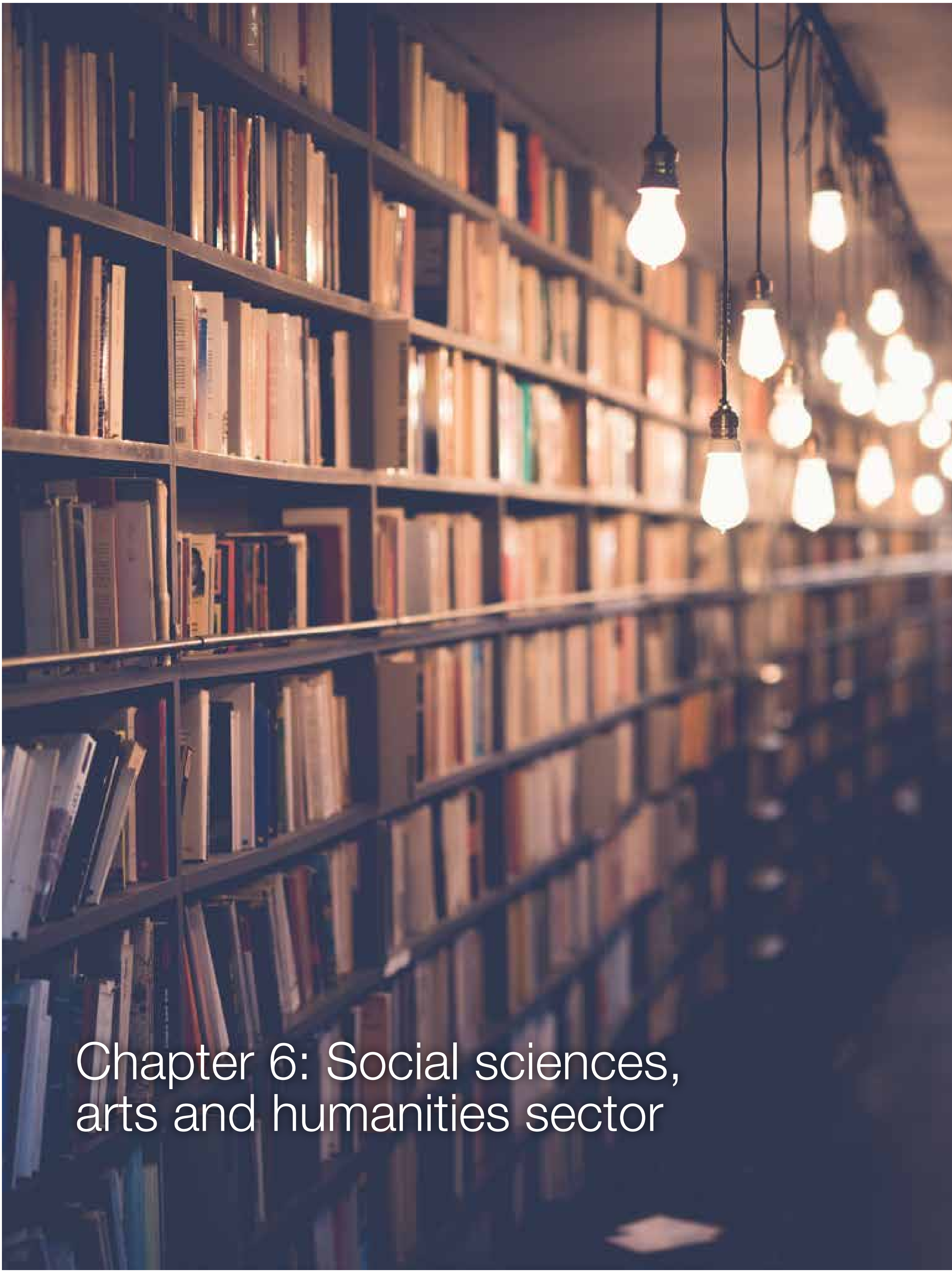
As discussed in chapter 3 the rapid increase in data volumes and processing requirements expected over the next ten years is a critical challenge for all infrastructures. The scale of this challenge is already evident by the volumes of data already generated by international facilities such as CERN, ESRF and ESO.

Unprecedented quantities of data will become available from large-scale particle physics and astronomy infrastructures in the next few years. When the SKA begins operations in the mid-2020s it will need to process tens of Terabits of data every second. The large multidisciplinary facilities also face increasing demands as new facilities are constructed and existing facilities upgraded. The ESRF is likely to produce around 25PB of data per year when the EBS upgrade project is completed in the early 2020s. This brings associated increases in demand on the HPC used for modelling, simulations and analysis.

There will be an increasing need and international effort for such projects and experiments to exploit and deliver a diverse range of computing capability not available at any single site and early consideration of e-infrastructure requirements is vital.

Particular e-infrastructure requirements for the PS&E sector include:

- Co-operating across organisational, campus, project and national boundaries to provide the scale and diversity of computing resources required in a cost-effective way
- Linking increasingly affordable but high-data volume networked scientific equipment, such as electron microscopes, to national centres for processing and long-term storage of data
- Enhance the ability of remote scientists to carry out ‘real-time’ research activities such as remote experiment control at national and international experimental facilities. Rapid access to data outputs also enables efficiency gains obtained through the ability to identify and resolve errors or make parameter adjustments during the experiment window.
- Increased coding efficiency and move towards intelligent solutions such as improved algorithms and machine learning
- Keeping abreast of wider developments and how best to utilise these for research computing, e.g. computing technology developments and services such as public/ commercial cloud provision



Chapter 6: Social sciences, arts and humanities sector

This chapter describes the emerging themes within the social sciences, arts and humanities (SSAH) sector. Rigorous research across the SSAH disciplines is pivotal to inform and address many of the major challenges of our time. Together social science and the arts and humanities sector ensure that there is a greater understanding of the world around us. This helps diverse communities to live rich, socially engaged and productive lives.

The increasing importance of these disciplines is evident in the Industrial Strategy missions and in UK government departments' Areas of Research Interest, the main research questions facing government departments[68].Today our economy is over 80% services, and growth is driven by how effectively those services understand and engage with people. Social science is critical in developing our ability to deliver effective public services that are cost-effective and increase social cohesion, an area in which the arts and humanities also play a vital role in understanding how we undertake our responsibilities to society and humanity globally. The UK's reputation as a creative powerhouse rests on the new knowledge and cultural experiences generated by the arts and humanities. Our rich and varied heritage makes the UK distinctive and will continue to do so in the coming decades. With the fast-growing publishing, TV, film, fashion, music and gaming industries, alongside world-renowned theatres, galleries, libraries and museums – all central to the UK's economic future – the arts and humanities are instrumental in helping to shape skills, ideas and products at the interface between creativity and technology upon which that future turns.

This work has been led by ESRC and AHRC. UKRI is the major source of funding for large parts of the sector through capital investment, grant support or universities formula funding. However, the initial analysis also demonstrates how the sector, in particular the arts and humanities, finds significant funding through non-UKRI government funding, philanthropic sources, charities or private sector support. The SSAH 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 possesses in-house capacity to carry out and lead research independently in their chosen field or discipline[69].

To develop these emerging themes we have drawn upon a range of inputs including consultation workshops, a small expert advisory group created for this purpose, guidance from existing advisory structures within UKRI and a number of earlier independent strategic reviews and recommendations, including the UK Strategy for Data Resources for Social and Economic Research 2013–2018[70], the Administrative Data Taskforce Report December 2012[71] and more recently the Longitudinal Studies Review[72].

6.1 Definitions and scope

HESA data shows that over a third of research staff in UK universities are part of the SSAH sector[73]. This sector includes:

- Economics
- Cultural studies
- Social policy
- History and heritage
- Social statistics
- Management and business studies
- Design
- Literature
- Archaeology
- History
- Philosophy
- Languages and linguistics
- Criminology
- Law and legal studies
- Political science
- International studies
- Creative and performing arts
- Digital Humanities

Within the work for the progress report, we have considered:

- Major data infrastructure investments in the social sciences, for ingest, curation, archiving, linkage and secure access provision for research data including nationally representative surveys and internationally renowned longitudinal population studies
- Organisations performing research into methodologies, such as the National Centre for Research Methods

Infrastructures in the arts and humanities fall broadly into the following categories:

- Physical collections (including artefacts and larger physical structures such as archaeological sites) and their storage facilities
- Archives (including both physical objects and digital artefacts)
- Digital infrastructure (including digital record creation, digital data storage and tool sets)
- Libraries
- Laboratory facilities for heritage science and archaeology

6.2 Understanding the landscape

Research in this sector depends heavily on a wide range of infrastructures and a degree of fragmentation exists. This diversity means that categorisation can only be done in broad terms; however, we have identified some distinct groupings.

Infrastructures in the social sciences include:

- Infrastructures that focus on data collection and/or data services, such as curation, linkage and access to data. Some are very long-standing, with increasing research value provided from decades of data collection. Examples include Understanding Society, the world's largest nationally representative household panel survey, The Cohort and Longitudinal Studies Enhancement Resource (CLOSER), which maximises the use, value and impact of UK longitudinal studies and The Administrative Data Research Partnership (ADRP), which enables linkage of and access to government administrative data for research purposes.
- Infrastructure investments that have a shorter lifespan or provide specific capability in a particular area. For example, the British Election Study (see case study).
- Infrastructures that have a much broader remit and provide an important capability to help address a wide range of social, health and public policy issues. By collecting and analysing data on people and their lives over time, these infrastructures provide capability to also help address currently unknown issues which may emerge in the future. For example, the Centre for Longitudinal Studies (CLS) has collected and curated data on three generations, from birth to adulthood, providing data (including genetic) on most aspects of their lives and therefore enabling researchers to truly understand the interplay between social environments and biological outcomes.

The British Election Study (BES)

The ESRC-funded BES is one of the longest running election studies world-wide and the longest running social science survey in the UK. BES is a non-partisan, objective, independent study providing world-class data and research into the 2015 British general election, and which has covered every British general election since 1964. It has made a major contribution to the understanding of political attitudes and behaviour over nearly 60 years. The Report of the Inquiry into the 2015 British General Election Opinion Polls drew on BES data and analyses and caused leading polling experts to change their methodology. As a direct result of advice from the BES, major polling organisations ICM and TNS adopted turnout weighting methods and YouGov also increased efforts to recruit non-voting respondents.

Arts and humanities research infrastructures include many long-established institutions and collections as well as cutting-edge technical equipment and sophisticated digital infrastructure.

Libraries and Archives Infrastructure: The United Kingdom libraries and archives sector is a key national infrastructure holding a wealth of heritage and contemporary information informing research across all disciplines. UK is home to around 3850 public libraries and 950 academic libraries, including the British Library, one of the largest collections in the world. The National Archives is the official archive and publisher for the UK Government, and for England and Wales, and guardian of some of the nation's most iconic documents, dating back more than 1,000 years. The increasingly multimodal collections held in these institutions present a priceless and irreplaceable asset for future research.

Historical, cultural and heritage: All material pertaining to the past is potentially an object of research and the data it represents is part of the infrastructure. The study of history, culture and heritage is principally dependent upon collections held in physical and digital libraries, collections, archives and museums. For example, sociological surveys, such as Mass Observation (began 1937), are regularly mined by historians and sociologists investigating changing social attitudes and identities. The challenge for arts and humanities research is one of selection and management. Administrative data generated by local and national government or other institutional bodies (census data, taxation records, poor law records, ecclesiastical records, judicial records, vital registration records) allow researchers to study questions ranging from economics to demographic change or the historic exercise of social control. Personal data (correspondence, diaries, account books, surveys etc.) relating to individuals from the past have often been deposited in local or national repositories. Researchers are increasingly aware of, and sensitive to, questions concerning the materiality of physical objects and structures, which requires engagement with the object/building itself and draws on infrastructure of the physical sciences held in museums and other collections.

Archaeology and heritage science draws heavily on a range of physical and biological science methodologies, requiring laboratory-based infrastructure to study, for example, previously inaccessible artefacts such as ancient scrolls through advanced scanning techniques.

The **creative and performing arts** are dominated by practice-based research, which presents further challenges in terms of new materials/products/performances that must be collected and curated or captured and recorded using infrastructures. Researchers and practitioners frequently draw upon historic collections such as the Victoria & Albert Museum to help interrogate their own practice and for inspiration see, for example, the Clothworkers' Centre for the Study and Conservation of Textiles and Fashion.

Languages and literature rely principally on historic and contemporary collections held in libraries and archives (print, oral testimony, film). While much of this research is qualitative and reliant on digitisation of sources in English and other languages, analysis of texts and recorded speech through corpus linguistics methodologies is increasingly reliant on AI and machine learning for example in forensic linguistics. Translation studies are increasingly using Machine Translation, a key infrastructure, in which further investment is still required.

Digital Humanities Ever growing and evolving digital collections, data-driven research programmes, and digital partnerships provide us with huge opportunities to rethink what constitutes arts, humanities and social science research. Digital technology has changed the way we collect, map and represent research findings, collections, populations, buildings and environments. It has changed the way we can connect with researchers and other audiences on a global scale. Datafication of text, image and sound coupled with approaches to allow pattern recognition, statistical analysis and other forms of software-based interrogation has opened up the possibilities for new forms of digital research with approaches such as use of artificial intelligence, concept and entity recognition, and virtualisation.

The complexity of 'born-digital' archives (lives and narratives that are created in digital formats) and the challenges of archiving for discovery across many different formats raise significant questions about how to preserve, catalogue and make available these materials discoverable and accessible in a coherent fashion, in perpetuity. As the British Library and other institutions continue to capture and archive many forms of 'born digital' lives and narratives, research in this domain can help us unpick and interrogate technological, ethical, linguistic, ethnographic, legal, privacy and rights issues. This is a fertile area for the arts, humanities and social sciences to explore natural crossovers with other research domains.

SSAH infrastructures include IROs which are nationally, and often internationally, significant as leading cultural and heritage institutions such as the National Museums Scotland and the Victoria & Albert Museum. The international reputation of these collections brings its own challenges of preservation and conservation. Digitalisation has done much to preserve a fragile infrastructure of manuscripts, printed materials and objects, which would be damaged by frequent handling. However, a digital proxy is not always sufficient for research purposes, nor does it necessarily meet the expectations of visitors. Even when digitalised, the original objects and artefacts cannot be disposed of which presents further challenges of storage and access.

Data infrastructures provide cost-effective resources for investigating a wide range of issues, including the current and historic relationships between policies, environments and behaviours, and social, cultural economic and health outcomes. These research resources enable deeper understanding of people's changing lives and attitudes, in both the past and present, providing a robust evidence-base for policy and practice as well as, importantly, the generation of new knowledge. Enquiry in the SSAH sector is reliant on access to timely and up-to-date high-quality data. SSAH data is generated from a range of sources; some (like surveys and laboratory experiments) are specifically designed for research, while others are collected and made available for research (such as administrative data records, records, archives and collections and social media data) but not created originally for that purpose. Data infrastructures funded by UKRI, through ESRC and AHRC, are used extensively in government and are a significant attraction for global research talent. Such data investments cannot be paused and re-started as their value depends on the ongoing relationship with participants, the frequency of data collection, and the continuous alignment of data collection, new tools and methods, with key research and policy.

6.3 Key messages and emerging themes

Research and innovation infrastructure requirements for this sector fall into three main categories:

- **Data collection –** collecting new data for research purposes, for example, collecting specific data in relation to a representative sample of the population over time
- **Data services –** to provide secure access to research ready data from a variety of sources, activities include ingest, curation, archiving, linkage, data analytics, user guidance and secure access
- **Physical and digital libraries, collections and archives**
- **Facilities for archaeological and heritage science research**

Underpinning these categories is the need to simultaneously develop appropriate methods to ensure that researchers are equipped with the skills that they need to conduct robust enquiry. Like many other research disciplines, the sector has undergone a step change in the way that it collects, accesses, links and analyses data. However, as discussed in chapter 3 there is a shortage of digital and computing skills, which hinders further step-changes in capability.

SSAH data infrastructures

Data infrastructure spans existing and historic datasets, innovative and potentially transformative linkage of existing data, and data services where data is curated in safe, secure and anonymised forms for re-use. The ESRC's large-scale studies of people over their lifetimes and representative samples of the population are extremely valuable. They tell us about how people's attitudes and behaviours change over the course of their lives and across generations. They also tell us about how society has adapted to complex changes in the world. The scale and quality of the data allows researchers to understand how attitudes and behaviours affect outcomes, with important implications for people's lives and life chances. The data allows these questions to be examined over a long time frame, whilst highlighting short-term fluctuations or deep-seated patterns in areas such as health or fertility for example. Researchers will continue to require access to data infrastructures that capture, store, process and provide appropriate and supported access to the data generated. This ensures the data is fit for research purposes and prevents expensive and wasteful repetition of data collection. Interoperability between data infrastructures is vital, so that projects using different types of data can be undertaken. This is a challenge for SSAH where many users are the general public or from disciplines that do not have the grounding in complex data science needed to make best use of the resources

The services required to support user access include (but are not restricted to) ingest, curation, storage and archiving, user guidance, linkage, safe settings, secure access to de-identified data and data analytics. Solutions to these issues were described in ESRC's recent longitudinal studies review[74].

Research on people and their behaviours and attitudes tends to rely on personal data, and the collection, processing and storage of that data comes with specific ethical and legal requirements. These requirements evolve over time, as legislation changes and as the types of data that become available and new research ideas for using that data emerge. A joined-up and efficient national infrastructure for social science data would help to manage these challenges efficiently. In addition, there are relatively few commercial companies capable of the necessary field work and large-scale survey collection. The complexity and low margins for such work creates limited incentives for new market entrants.

The scale of digitalisation that is still required across much of the arts and humanities infrastructure is challenging. Whereas the entirety of some collections in national institutions (for example, the National Gallery) have been digitalised, other national institutions (for example English Heritage) have only partial coverage and some collections exist only as a digital inventory. The problem is even more pervasive beyond the national institutions. At present, common data standards are only patchily implemented and further work needs to be done on facilitating interoperability. Linkage across different collections will require either a common system of metadata or use of AI to enable different collections to connect with each other as well as greatly improved cataloguing.

As set out in chapter 2, AI and machine learning bring new opportunities for methodology development, data linkage and understanding of causal estimates, which are more relevant for policy and improving outcomes. Application of these tools to historic data sets is already providing and raising significant insights into historical processes and raise new research questions.

A shared view of standards and operational models for data heavy infrastructures across all sectors will mean that infrastructures are generally better placed to apply good practice and learn from each other. Adapting to new methods or approaches will allow infrastructures to respond flexibly to changing research or strategic priorities. The longitudinal studies review recommended a number of new data infrastructures including a new birth cohort and exploring the development of an administrative data spine. Greater access to administrative data will allow innovative approaches by design, as well as tracking key groups (for example, younger cohorts). It also recommended the continued development and enhancement of existing infrastructures (including Understanding Society), and various cohort studies and enhancement resources that enable access and linking to data, as well as methodological developments and training.

Future strategic investment in data infrastructure must ensure that we can provide the highest quality data in the most cost-effective way. We need to be in a position to strengthen and, where necessary, conserve our much-used existing infrastructure so that it is fit for growing and evolving demand[1], while building next-generation data resources, skills, tools and methodology for research data that will support cutting-edge UK social science and arts and humanities research in the future and ensures connectivity and interoperability with data resources in other disciplinary fields.

Archangel

Archives and memory institutions are founded on the principles of public trust, neutrality and objectivity. Today's digital age creates new challenges around safeguarding of such data - how can the public be sure that digital content is unaltered from the original when released? What are the implications of minor losses of data fidelity one hundred years from now? The Archangel project aims to ensure the long-term sustainability of digital archives through the design, development and trialling of blockchain technology. It also seeks to determine how archival practices, models and public attitudes could evolve in the presence of a trusted decentralised technology, to prove content integrity and ensure open access to digital public archives. The project is a multi-disciplinary partnership between the University of Surrey, the National Archives and the Open Data Institute.

In addition to the drivers for change described in chapter 2, critical future drivers for SSAH infrastructures include:

- Making the best use of new forms of data and different technologies for collecting data, for example, wearable technologies or remote sensors. Technological innovations will also support greater secure remote access to data, for example through blockchain and other distributed ledger technologies.
- Changing public perceptions of personal data use and the future regulatory and legislative environment. Infrastructures can play a role in shaping this future.
- Methodological innovations and data science skills, including innovation within the private sector or other disciplines.
- Advances in the field of heritage science and archaeology require investment in laboratory space and equipment to support physical and biological science research. Facilitating sharing of such significant investments across IROs and with smaller museums to provide a national service will be essential.

Physical and digital collections, archives and libraries

Common challenges for all infrastructures include signposting or discovery of materials, provision of access, including remote access via digitalisation and facilitation of the ability to search across collections and archives. The following tables summarise the emerging themes from our work so far based on a wide range of important social, economic and cultural issues facing the UK and global society. For each theme we present information on the specific and generic challenges associated with it and the infrastructure capabilities which may address those challenges. There are future data and infrastructure needs that cut across a number of the themes, and while the extent of the need may vary depending on the theme focus, they remain relevant to all.

- Appropriate data solutions to support the creation (including digitisation and retrospective metadata creation), storage and manipulation of large data files and collections
- Data integration platforms to support access and data linkage between data sources and types and across the academic, policy and industry communities (including safe settings)
- Methodological innovations to enable more efficient and robust analyses
- Strengthening of the quality and scale of infrastructure and skilled workforce (industry/policy/academic) to support innovation and evidence informed policy and greater public benefit

1 Over 20% of registered users of ESRC's UKDS are from disciplines outside of social science, including Medicine, Engineering, Biological Sciences and Environmental Sciences.

- Ethical and legal investment to ensure research and regulation keeps pace with emerging data access and shapes legislation into the future
- Investment to ensure new solutions provided by AI and machine learning do not simply perpetuate bias and historic patterns of discrimination within data collection processes

Theme 1: Economics and productivity

The productivity of a nation is directly linked to its overall economic performance and to citizens' living standards; strong productivity is seen as a key contributor to economic growth. With productivity well below that of peer nations and attendant lagging wage growth, understanding and stimulating productivity is arguably the UK's biggest economic and social challenge. Addressing regional inequalities, skills shortages and changing labour markets, particularly in the economic and political context of EU Exit, are crucial considerations for productivity and sustainable, inclusive growth. Moreover, we need to understand and address the changing macroeconomic context, stability of our financial systems and the future of our international trading relationships under a changing geopolitical climate. The Industrial Strategy sets out a long-term plan to address these issues and how research and innovation infrastructure can inform delivery.

<table>
<tr><th colspan="2">Theme 1: Economics and productivity</th></tr>
<tr><th>Science, research and innovation challenge</th><th>Potential capability required</th></tr>
<tr><td>Economic and productivity challenges
Addressing a range of economic and productivity issues, including but not limited to:
• Future of work
• Increase in automation and AI
• Productivity
• Worklessness, the gig economy and labour market inequalities
• Distributional effects
• Markets and market failure
• Improved cultural understanding of target markets for UK</td><td>Broad-based data to enable us to study the major interdisciplinary research and policy challenges of our day 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)
• Language skill and translation capacity to understand other markets and culture in which they operate

For example, as currently provided by:
• The ADRP
• Workplace Employee Relations Survey (WERS)
• The Skills and Employment Survey (SES)
• UK Data Service (UKDS)
• CLS
• CLOSER
• Business and Local Government Data Research Centres
• Understanding Society
• Creative Industries Policy and Evidence Centre
• European Social Survey</td></tr>
</table>

Theme 2: Next generation public services

Public services are facing considerable challenges including the ageing population, budgetary pressures, adoption of new technologies and the administrative uncertainty surrounding EU Exit. Many of these challenges require complex, multi-partner solutions and need to be 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 the right types of data in timely and safe ways.

Millennium Cohort Study

The Welsh Government used research from the Millennium Cohort Study to show that the proportion of adults and children not maintaining a healthy body weight is increasing. The research findings were used in The Welsh Government's All Wales Obesity Pathway in 2010 to help people achieve a healthy weight. The Pathway sets out a four-phase approach to manage obesity in Wales. It is also a tool for Local Health Boards in Wales to review policies, services and cross-departmental working.

Theme 2: Next generation public services

Science, research and innovation challenge	Potential capability required
Next generation public services challenges Addressing a range of social policy issues, including but not limited to: • Pressures on land and housing • Education • Criminal justice • Transport and infrastructure • Welfare • Ageing society • Digital inclusion • Physical and mental health and health-related behaviours • Social care • Understanding and mapping linguistic make-up of cities to develop services that are fit for purpose	Comprehensive data collection on people and their lives, including: • Attitude surveys • Household surveys • Cohort and longitudinal surveys For example, as currently provided by: • The CLS birth cohorts • English Longitudinal Study of Aging • 1946 National Survey of Health and Development cohort • Understanding Society • The ADRP • The UKDS • CLOSER • The Linguasnapp' app for mapping languages for major cities

Theme 3: Changing world

There are signs that long-established conceptions of how democratic politics and governance works are being disrupted, for example:

- The apparent loss of legitimacy of institutions such as established political parties and some mass media
- The shifting impact of educational background and regional, ethnic and cultural identities on political allegiances
- Increased capacity to mobilise protest through social media
- The diminished capacity of democratically-elected politicians to exert leverage over a diverse set of private, public and third-sector bodies that now deliver public services
- The challenges to liberal-democratic government norms through security threats arising from domestic and international terrorism and cyber-crime

In an interconnected world, few societal challenges are either distinct from, or unconnected to, wider global socio-economic, environmental and technological changes. In the context of the changing political context globally and the UK's changing relationship with Europe (and consequently its relationships with other parts of the world), policy makers, businesses and charities alike require the best possible evidence base and cultural understanding for informing interventions and tackling shared global challenges.

Theme 3: Changing world	
Science, research and innovation challenge	**Potential capability required**
Changing world challenges Addressing a range of issues relating to the changing world, including but not limited to: • Migration and conflict • Modern slavery • Corporate power shift or geopolitical changes • Role of state or trust in institutional frameworks • Divisions in society or polarisation of views • Identity politics • EU exit	Comprehensive data collection on people and their lives and values, including: • Attitude surveys • Migration data • Cohort surveys For example, as currently provided by: • British Attitudes Survey • The British Library, the National Archives and other library and archival collections • Understanding Society • The CLS cohorts • CLOSER • UK Labour Force Survey • The ADRP • European Social Survey

Theme 4: Addressing environmental challenges

Climate change is one of the most pressing challenges facing society today and the Industrial Strategy Clean Growth Grand Challenge is focused on developing clean energy technologies. The demand for research evidence to inform our understanding of, and response to, these unprecedented global changes has never been greater. Furthering our understanding of individual, cultural, political and corporate dimensions and interactions, will be essential to drive the extensive social, structural and systemic change that is required. Data is needed to adequately assess how to change attitudes and behaviours so that we can make the step change needed to move from people having an awareness and understanding of global change to seeking sustainable and equitable solutions, to making better choices and taking action: action to reduce the scale of the changes we face, increase societal and economic resilience to those risks, and tackle poverty whilst ensuring we are living within critical planetary boundaries.

Theme 4: Addressing environmental challenges	
Science, research and innovation challenge	**Potential capability required**
Environmental challenges Addressing a range of economic and social issues relating to the environment, including but not limited to: • Social and cultural attitudes and behaviours toward the use of scarce resources (e.g. energy, water and land use) • Regulatory or legal frameworks • Failure of markets to address environmental issues • Corporate responsibilities	Comprehensive data collection on people's attitudes and behaviours (current and historic), as well as the behaviour of firms: • Attitude surveys • Consumer and transactional data • Environmental monitoring data • Historic and archaeological data sets For example, as currently provided by the: • British Attitudes Survey • The ADRP • Consumer Data Research Centre

Theme 5: Creative economy

One of the UK's most dynamic sectors, the creative industries are growing at almost twice the rate of the wider economy and they are estimated to be worth around £90 billion a year[75]. Based on a long tradition of cultural expression through music, literature and the performing and visual arts, it now includes the advertising, architecture, design, publishing and fashion industries, as well as the film, media and video gaming sectors. The opportunities arising from the 'tech meets culture' also underpin the recent DCMS report *Culture is Digital*[76], which described the blurring of boundaries in the areas such as virtual curatorship and video games, as well as identifying new opportunities for collaboration between business and cultural organisations. Almost 2.1 million people are employed directly in creative industries, with a further million in the wider creative economy, translating as one in every eleven UK jobs and the Industrial Strategy Creative Industries Sector Deal is investing across the lifecycle of creative businesses British musicians, artists, TV programmes, fashion brands, video games and films are household names in many nations around the world, proving that domestic success can be translated into global impact. The UK is also recognised as one of the best markets in the world for forecasting and generating emerging trends and is seen as a key global influencer in creativity and innovation.

As digital technology continues to open up new ways to imagine, create, distribute, consume and participate in creative work, the future success of this crucial sector must be underpinned more than ever by risk-taking, innovative R&D. Only by investing at an early stage in new products, services, creative content and experiences can we be sure to maintain the UK's status as a world leader, to exploit the opportunities provided by world-class intellectual property and to identify and develop our potential in emerging fields.

The Creative Industries Policy and Evidence Centre (PEC) will be an independent voice to provide analysis, evidence and research to stakeholders in the creative industries. The PEC will facilitate collaborations, connections and research to form a detailed understanding of the creative industries so that future policy and strategy can be informed by world-class insights. The consortium brings together industry and policymakers at national, regional and local levels, and will draw on the expertise of organisations such as the BFI, Creative England, the Work Foundation and Tech City UK.

Theme 5: Creative economy	
Science, research and innovation challenge	**Potential capability required**
Creative economy challenges • New business models and Intellectual property • Investment • Skills shortages including languages • Equality, diversity and inclusion • Collaboration models • International trade	Comprehensive data collection on the sectors within the creative industries and the broader creative economy. For example, as currently provided by: • Creative R&D partnerships (funded under Creative Industries Clusters Programme) • Creative Industries Policy and Evidence Centre (funded under Creative Industries Clusters Programme) • AHRC Creative Economy Programme • Centre for Cultural Value

Theme 6: Understanding and maintaining cultural heritage

The UK's national museums, galleries, libraries, archives and historic places constitute a major part of the infrastructure for arts and humanities research; individually they drive tourism and economic development, play key roles in placemaking and support schools and university education. The heritage tourism industry draws significant economic benefits to the UK. In 2016 in England alone, it generated £16.4 billion in visitor spending, directly employing over 275,000 people and contributing £11.9 billion GVA to the economy. In 2013, it was estimated that Britain's tourism industry will be worth over £257 billion by 2025, just under 10% of UK GDP and supporting almost 3.8 million jobs[77]. Our cultural and heritage sector is also an essential constituent of the UK's soft power. Social benefits are increasingly apparent, including improvements to mental health and well-being, derived from engagement with heritage and a sense of connection to place.

The heritage sector, in collaboration with HEIs, produces excellent cross-disciplinary research. The impact of this work could be transformed through greater collaboration across institutions, realising the potential of a joined up 'national collection' as highlighted in the Mendoza report[78], DCMS's Strategic Review of National Museums[79] and in the 2017 Culture is Digital report[80]. These reports highlight the tendency for heritage assets to be siloed in individual organisations, isolating related collections and preventing synergies of sharing. Knowing who holds what resources, where they are held and making connections between collections is labour-intensive and an inefficient use of time that would be better spent developing the research potential of collections. However, digital technology, AI and machine learning presents the opportunity to connect individual collections together, search across them and make them more accessible to both researchers and the public, enhancing their international reach and influence.

Theme 6: Understanding and maintaining cultural heritage	
Science, research and innovation challenge	**Potential capability required**
Understanding and maintaining cultural heritage • Physical preservation and conservation of fragile objects • Ensuring access while also minimising risk to collection (e.g. for physical sites) • Incomplete or non-existent digitalisation • Absence of common standards or language used in metadata of digital catalogues • Physical storage space for an ever-increasing body of artefacts • Ensuring that cultural heritage that is recorded and preserved in infrastructure reflects diversity of modern society • Broadening access to a wide range of users	Comprehensive data collection within the cultural heritage sector. Interoperable data services to provide secure research access to the data listed above, including: • Ingest • Curation • Storage and archiving • Cataloguing • User guidance • Linkage • Safe settings • Secure access to data (de-identified where appropriate) • Data analytics

Theme 7: International development

The demand for research evidence to inform our understanding of, and response to, unprecedented global changes has never been greater. Furthering our understanding of individual, cultural, political and corporate dimensions and interactions, will be essential to drive the extensive social, structural and systemic change that is required. Social science and the arts and humanities is fundamental to understanding how to change attitudes and behaviours so that we can make the step change needed to move from people having an awareness and understanding of global change to seeking sustainable and equitable solutions, making better choices and taking action. There continues to be a need for quality, rigorous and usable data in development contexts, which poses a particular challenge in an environment where diverse actors take different approaches, using varying methodologies and producing often inaccessible data. Language skills and sensitivity to language and cultural contexts depends upon arts and humanities methodologies and infrastructure.

Theme 7: International development	
Science, research and innovation challenge	**Potential capability required**
International development challenges Addressing a range of economic and social issues arising in developing countries, including but not limited to: • Educational progress and skill development • Inequalities in educational, social and economic spheres • Environmental challenges emerging from rapid economic development • Language skills and cultural understanding	Access to quality, rigorous and usable data in development contexts. Infrastructures that support the gathering and understanding of research evidence to inform our understanding of, and response to, unprecedented global changes. Infrastructure that supports our understanding of individual, cultural, political and corporate dimensions and interactions, will be essential to drive the extensive social, structural and systemic change that is required. For example: • Young Lives Study • The ESRC Impact Initiative

6.4 E-infrastructure and data

The SSAH sector has a strong focus on the organisation and distribution of data, information and knowledge for research. As in all research endeavours, this is increasingly in the form of digital objects. Some of them have been collected as research data; some are digitised forms of objects that were originally stored in another form (records, archives, digitised versions of physical collections, other recordings such as sound). A number of infrastructures heavily used by researchers in the SSAH sector consider their primary discipline to be e-infrastructure (for example, the UK Data Service, some components of major libraries).

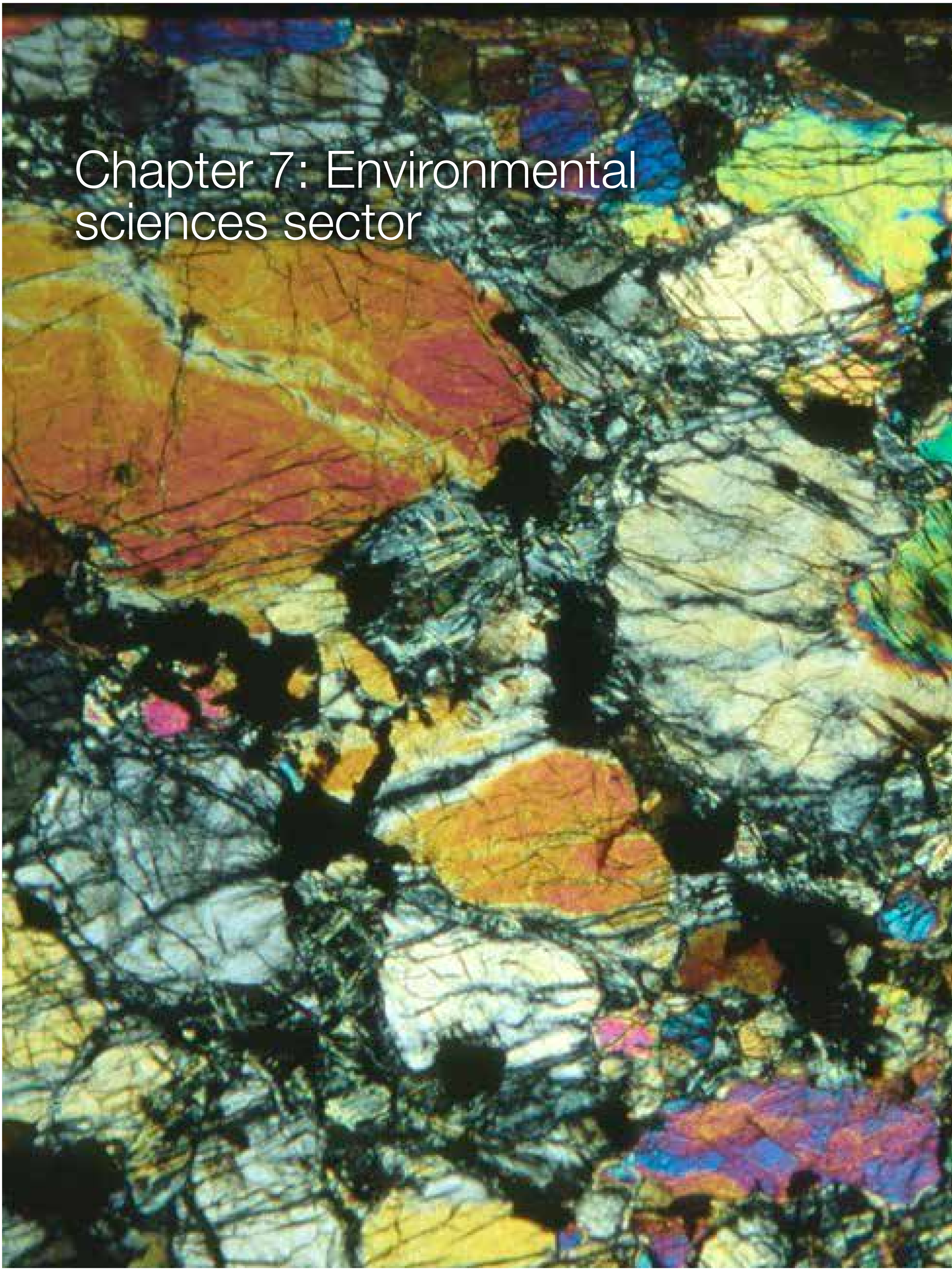
Future needs are therefore strongly driven by requirements for access to data. As discussed in chapter 3, not all data can be published openly. Data management needs to be consistent with the relevant legal, ethical, disciplinary and regulatory frameworks and norms in place at the time. The overarching challenge to the future of any data infrastructure for research is how much the principles of open research can be supported. As such, the ambition should be to build an ecosystem that supports the FAIR philosophy – making all outputs findable, accessible, interoperable and reusable for humans and machines.

Community discussions on future e-infrastructure needs to highlight requirements for more comprehensive access to data on the key social patterns of life (for example, anonymised data from telecoms and mobile operators and transport data) and social media data at scale. Our ambition is to draw on existing and planned infrastructures and investments made by the research councils and others to build a critical mass in capability, to access and analyse these new and emerging forms of data.

Mechanisms to link these datasets to administrative data can provide rich insights into how patterns of behaviour link to health outcomes. This is urgently needed if the full value of these data are to be realised. Further exploration of 'trusted researcher' models for secure data access and the exploring the notion of Data Trusts would also be beneficial[81].

The SSAH sector derives significant value from data that were not originally generated for research purposes, and considerable effort is required to ensure that these data are usable for research ethically, legally and on a practical level. As with all other sectors this increasing reliance on large volumes of data drives an increasing need to access high-performance computers, for example multi-scale predictive modelling or large-scale visualisations.

Chapter 7: Environmental sciences sector


BGS © UKRI

This chapter describes the emerging themes within the environmental sciences sector. Innovative infrastructures for environmental science can transform the UK economy by enabling clean growth in harmony with our environment, balancing economic and environmental gains and costs to help the UK thrive now and into the future.

We depend on our environment for shelter, heat, light, food and water, and other essential earth resources such as minerals. Sustaining planetary health depends on our ability to measure and model how and why our environment is changing, and to predict how it may evolve in the future. The infrastructures that support research and innovation within the environment sector enable the delivery of evidence that users of research need to design appropriate mitigation and develop a resilient society through adaptation and preparedness.

UKRI provides a platform to deliver shared outcomes from the environment sector, which is spread across organisations such as HEIs, government departments and agencies, public sector research establishments such as the Met Office, 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.

This chapter draws both on NERC's internal capital investment planning processes and a review of current and future needs for its services and facilities, as well as a range of stakeholder engagements, led by NERC and/or the Met Office. The infrastructures that support research and innovation within the environment sector are diverse, including ships, aircraft, Earth orbiting satellites, high-performance computers, advanced modelling, data assimilation and analysis software, laboratory-based analytical facilities, in situ measurement networks, farm- and landscape-scale experiments, and collections such as geological cores/geoscience data sets. NERC also funds and maintains infrastructure in the Antarctic to support the dual role of the British Antarctic Survey: to manage a world-class science programme and to deliver the UK's strategic footprint in the British Antarctic Territory, South Georgia and the South Sandwich Islands.

7.1 Definitions and scope

The environment sector includes terrestrial, freshwater, marine, science-based archaeology, atmospheric, climate and polar sciences, together with Earth observation and computational modelling. Environmental scientists study and monitor the physical, chemical and biological processes that shape the natural world upon which our planetary health depends, and they predict its future evolution in the context of human pressures on the natural environment, especially climate change, pollution and waste. Increasingly, environmental research is delivered using infrastructures that cut across 'compartments' of the earth system and are designed, supported and delivered in partnership with other research funders and research users.

7.2 Understanding the landscape

There has been an evolution in environmental sciences in recent years, away from a position of just identifying problems into the realm of proposing and implementing interventions and solutions, along with the analytical tools to assess the progress of those interventions. The environment sector, science and services, now plays a pivotal role in addressing 21st century challenges. The development of environmental services provides a delivery mechanism for this. In this sector 2015 was a landmark year. The world endorsed the Paris Agreement, the first universal, global climate deal. The UK signed up to the Sendai Framework, to work together to achieve substantial reduction of disaster risk and losses in lives, livelihoods and health. Finally, the UN Sustainable Development Goals were agreed on, aiming to end poverty and hunger, improve health and education, make cities more sustainable, and protect oceans and forests. Positive outcomes can be achieved for nations at all levels of economic development by linking actions to improve resilience and to reduce environmental damage, all with improved health and well-being outcomes[82].

__Current strengths__

The UK Environmental science community relies on access to high-quality infrastructure that needs to reach, observe, model and simulate all parts of our environment. The UK has particular strengths in:

- Remote research stations, such as Antarctic stations and logistics support. This is an example of the UK's current long-term integrated environmental observation, which requires maintaining an infrastructure in a geographically remote and harsh environment. The ability to develop, deploy and maintain a suite of innovative technologies including ice core drills, hot water drills, radars and automatic weather stations enables science teams to take measurements across the polar continent
- Large research observational platforms such as NERC's fleet of research ships and aircraft
- Long-term national and international observing networks that enable us to monitor variability and change and identify potential tipping points (e.g. RAPID-WATCH Atlantic Meridional Overturning Circulation, Weybourne Atmospheric Observatory, National River Flow Archive and Predatory Bird Monitoring Scheme)
- Partnerships that facilitate contributions and access to international facilities (e.g. Earth Observing Systems through the UK's research strengths), the international bartering of access to facilities such as research ships and the UK involvement in major international field experiments
- Small sensor development for remote sensing and flexible and innovative field measurements such as marine robotics; these have led to commercial spin-off and exploitation
- Expertise in the efficient and effective use of world-class HPC to solve societal problems
- State-of-the-art environmental modelling, simulation and prediction using physical models of complex systems, underpinned by 'big data' systems (e.g. NERC JASMIN), informatics, AI and machine learning
- Curation of long-term records to measure and monitor environmental variability and change
- The collections on which observations are based, such as ice cores, geological cores, DNA and collections of plants and algae, all of which require specialist storage infrastructures and curation to allow access for researchers

istock

Restoring our protective ozone shield

NERC-funded Antarctic bases, research ships and aircraft were crucial to finding the hole in the ozone layer. The ozone layer naturally protects the Earth from harmful ultraviolet (UV) light and NERC scientists were the first to discover that this was being depleted high in the atmosphere. Without this research it would have taken an estimated five to ten years longer to discover the ozone hole, delaying the Montreal Protocol – the global agreement to phase out ozone-depleting substances – and increasing the negative effects of UV damage. This early implementation saved thousands of lives and lowered food prices, saving the UK an estimated £1.3 billion every year.

7.3 Key messages and emerging themes

Environmental science provides important knowledge and insight to many economic and industry sectors: including food and water, energy and waste, transport and infrastructure and defence and healthcare. Environmental research also impacts policy and practice in a number of ways, within which major infrastructure provides a vital underpinning capability. For example, government policy and public services are informed by the UK's strength in environmental prediction across scales, from hours to decades and from the local to global. These predictions are based on complex model simulation systems running on state-of-the-art supercomputing platforms and ingesting real-time observations from across the world, e.g. numerical weather prediction and flood forecasting models aligned with increasingly sophisticated field observations.

Tackling the problem of plastic waste

Since Blue Planet II aired in 2017, public awareness of plastic waste has increased. Prime Minister Theresa May described plastic waste as "one of the greatest environmental challenges facing the world". Research ships and our Antarctic base facilities helped discover the problem of plastic litter in the oceans, air and soil, and revealed the harm from long-lived plastic pollution. This science informed the recommendations of the House of Commons Environmental Audit Committee and led to the government ban on plastic microbeads in cosmetics and personal care products in the UK from 2018. It also supported changes in US and Canadian policy and UN global policy advice in 2016.

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Through the stakeholder and community discussions to help develop this chapter, the following key messages have emerged:

- **Global societal challenges require global solutions.** Working in an international arena and partnering internationally is a key characteristic of the environmental science community and the infrastructures that support it. The landscape survey shows that 78% of the infrastructures collaborate nationally and internationally and 92% of infrastructures attract users from other countries.
- The **world-class environmental science** in the UK and the move from 'science' to 'science into services' positions the UK well in the international arena. For example, the UK has been influential on both climate change science and policy from the beginning, in particular through the IPCC where the UK provided lead authors across all working groups.
- Providing solutions to the challenges facing our planet requires **multi-disciplinary, multi-scale, whole system approaches** on a scale that demands major observational and digital infrastructures.
- New developments in **sensing technologies and autonomous measurement** and analysis will provide environmental information at unprecedented spatial and temporal

scales. Measuring systems capable of capturing environmental processes will be required, from the nanoscale to planetary, from seconds to millions of years and functioning in harsh and hazardous environments.

- Quantifying and understanding variability and change in the Earth system, to identify trends and deliver baselines to test projections of change and/or evaluate the outcomes from interventions, relies on the **continuity of observations and monitoring systems**.
- Environmental observations, simulations and predictions generate very large data volumes on a continuous basis that need to be interrogated, analysed and visualised in a timely way. This will require well-found big data systems and the development of **innovative data science**. The potential for AI and machine learning to provide environmental information is immense, provided the data science infrastructure is in place.
- At all scales, from the global to local, we rely on innovation in environmental **modelling, simulation and prediction**. These provide a computational laboratory for a growing cohort of environmental researchers who seek to understand how the complex Earth system works and how it is changing, to improve forecasting impending hazards and to deliver more robust scenarios of future climate change.
- Translating environmental science and information into **actionable advice** requires an understanding of the whole 'value chain' from hazard to impact and response, requiring interactions across science domains and sectors. The increasingly close cooperation between NERC and service providers (e.g. Met Office, Environment Agency and Natural Hazards Partnership) could be strengthened by further alignment of major infrastructures.

Technology drivers

There are opportunities for the environment sector to harness the convergence of the application of digital technologies to environmental science (e.g. cloud computing, IoT and more cost-effective sensors), efficient and effective exploitation of major HPC, development of world-class simulators of complex earth and environmental systems and data analytics and informatics.

Constructing a digital environment is a priority for infrastructure investment. The goal is to create a ubiquitous, geospatial and intelligent system, covering the land surface and subsurface, ocean, atmosphere and cryosphere, that is agile and interconnected at a variety of scales, and which has the capability to combine data from observations with synthetic data from simulation and prediction. A digital environment encompasses both the breadth of the technology (including instruments, sensors, observing platforms, supercomputing and simulation/prediction systems) and the capability to develop, deploy and apply the technology (including model and simulation/prediction system development, methods of data capture, analysis, visualisation and interpretation and combining and assimilating data sources within models to provide a holistic view).

Autonomous measurement in remote and/or inaccessible environments is a strength of this sector and an area of real innovation. Combining this with environmental modelling and simulation forms the basis for increasing the use, scope and sophistication which, for example, will enable us able to rapidly characterise emergency situations, such as volcanic eruptions, storms, floods, wildfires, earthquakes and oil spills.

Miniaturisation and automation of surface and satellite sensor technologies are also important. The trend is for more efficient and cheap monitoring capacity and the ability for it to be mobile. Rather than single, large Earth observation satellites, for example, increasingly there is a trend towards constellations of smaller satellites that can be provided at lower cost in greater numbers; the data of which can be combined to give both higher spatial and temporal resolution views and/or complementary observations in different regions of the electromagnetic spectrum.

Building a buzz about citizen science

Pollinators are central to our environment and economy: approximately 80% of British plant species rely on insect pollination, and pollinators are estimated to contribute up to £650 million per year to UK crops. However, pollinator populations are declining. The Big Bumblebee Discovery had three aims: to explore how different landscapes affect bumblebee populations, to engage children in research through a citizen science project and to teach children about the importance of pollinators. Around 13,000 children have been involved in the Big Bumblebee Discovery gathering a total of 26,868 individual insect sightings. The scientists integrated these observations, assessed their accuracy and used the data to analyse the impact of landscape context on overall bumblebee abundance. The Big Bumblebee Discovery also won the Third Sector Business Charity Award for Charity Partnership (short term) at the 2015 annual Business Charity Awards, being praised for the project's partnership and engagement.

Coupling these new developments in sensing technologies with developments in communications and power supply will enable a step change in how we will be able to provide environmental information at unprecedented spatial and temporal scales.

The rise of 'citizen science' is also important for this sector. It aligns with the requirement for more and better distributed networks of sensors, underpinned by step changes in the supporting communications networks and technology.

The following table summarises the emerging themes from our work so far. For each theme, we present information on the specific and generic challenges associated with it and the infrastructure capabilities that may address those challenges. The interconnectedness between these challenges is vital, and solutions will be achieved by taking cross-cutting approaches that address multiple challenges across multiple disciplines and sectors. We have divided the capability requirements into an overarching framework of observations, simulations and data/data infrastructure, although the intersections between these divisions are important. For example, simulation and observations inform one another when considering future needs.

<table>
<thead>
<tr><th rowspan="2">Science, research and innovation challenge</th><th colspan="2">Potential capability required</th></tr>
<tr><th>Capability to address the challenge</th><th>UK capability required</th></tr>
</thead>
<tbody>
<tr><td rowspan="3">1. Clean air solutions: finding solutions to improve outcomes for human health, well-being and the economy.</td><td>Point source and pathway measurements of emissions at high resolution.</td><td rowspan="10">Observational capability. There is an increased need for temporal and spatial, real-time and globally deployable observation systems to support real-time decisions, supported by real-time communications. This must support the wide temporal and length scales. These infrastructures must be adaptable to cope with advances in observational platforms and field tested to be reliable and robust to cope with harsh environments.

The challenge is therefore to design:
• Infrastructure that can be adapted to need and that makes use of technology in situ
• Sensors that meet different environmental needs and maintain consistency

This requires an investment in:
• Autonomous systems with:
o Increased endurance (further, longer, deeper)
o Distributed networks of multi-instrument packages
o Miniaturisation (low cost, high volume)
o Autonomous vehicles including multi vehicle deployment (swarms) and inter-vehicle co-operation
o Plug and play locations/quickly deployable (e.g. for emergency response) and specific to the deployment environment
o Automation in remote and extreme/harsh environments (e.g. under ice, sea bed, at high altitude)
o Power sources for automation

• Platforms with advanced instrumentation, including:
o Active and passive remote sensing platforms (which include biological and chemical sensors)
o High-altitude platforms (> 20km), from satellites to airborne platforms, with the opportunity to make more use of commercial platforms.
o Infrastructures that support satellite data, such as more mobile, distributed sensor networks and ground-truthing
o Land and subsurface platforms
o Scalable observation systems from soil microbial scale up to farm-scale platforms and experimental catchments

• Connected and interdependent data collection and gathering systems, while maintaining distinct individual data sets
• Maintaining/expanding the UK's contribution to international networks, e.g. ARGO, seismic and geodesy
• Maintenance of Antarctic infrastructure to support critical long-term polar observations (as well as maintaining the UK's Antarctic presence)</td></tr>
<tr><td>Ability to model the composition of the atmosphere under a range of scenarios.</td></tr>
<tr><td>Delivery of interoperable data across data types and scales.</td></tr>
<tr><td rowspan="3">2. Services for a changing climate: developing robust quantifications of the risks and impacts of climate change and extreme weather events affecting environments and society (e.g. business and infrastructure).</td><td>Sustained observations to quantify key processes that drive climate variability (e.g. melting ice, carbon feedbacks and sinks, ocean circulation).</td></tr>
<tr><td>Ability to model how these processes will be impacted by climate change. Develop robust quantifications of the risks and impacts of climate change and extreme weather events (e.g. storms, floods and droughts).</td></tr>
<tr><td>Delivery of interoperable data across data types and scales.</td></tr>
<tr><td rowspan="3">3. Multi-hazard risks: improved predictions and risk assessments of severe weather, hydromet, geo and cascading hazards.</td><td>Observations of key variables and processes, including emergency deployment of sensors into harsh environments/emergency situations Maintain contributions to international observing systems.</td></tr>
<tr><td>Modelling scenarios showing the impact of a combination of hazards and the vulnerability of key infrastructures.</td></tr>
<tr><td>Delivery of interoperable data across data types and scales.</td></tr>
<tr><td>4. Blue economy: delivering outcomes that will both support the effective management of the marine system and the sustainable expansion of the marine economy, both nationally and internationally.</td><td>Sustained marine observations and the use of new tools and technologies to observe the marine system (including aquaculture) and how stressors impact on it.</td></tr>
</tbody>
</table>

Key Observations | Simulation | Data/data infrastructure

Science, research and innovation challenge	Potential capability required	
	Capability to address the challenge	UK capability required
	Modelling under a range of scenarios to support decisions on the effective management of the marine system to support the expansion of the marine economy.	**Simulation capability.** Feeding in from observational infrastructure. A complex systems approach is needed for simulations and predictions, including a step change in modelling approaches (including earth system modelling), scenario testing and systems simulation, visualisation and connecting models to observation networks. Linking across scales can inform decisions. Demonstrators/test beds will enable us to pilot real-time forecasting. There is a need to use simulation for risk assessment across different timescales, requiring probabilistic predictions and scenarios. Greater resolution is required, alongside an investment in next-generation earth system modelling including through HPC investment (e.g. JASMIN). This will require ongoing investments in supercomputing, in model software and in prediction system development, such as in data assimilation and formal assessments of uncertainty.
	Delivery of interoperable data across data types and scales.	
5. Landscape decisions: providing the understanding of ecosystems and the services they provide at the landscape scale as well as the natural capital underpinning these.	Observations of changing land use and land management consequences and the ecosystems and the services they provide at the landscape scale.	
	New mathematics and modelling approaches for decision makers that need to balance the competing demands on land use.	
	Delivery of interoperable data across data types and scales; appropriate data visualisation and tools to support multivariate decision making.	
6. Sustainable food systems: includes both land and aquatic systems, at the farm and landscape scale, and incorporating supply chain impacts, the links between food production, water resources and GHG emissions, food system regulation and certification, and valuation of natural capital that underpins the food system and ecosystem services related to food systems and supply chains.	Observations of both land and aquatic systems (including wild capture), at the farm and landscape scale.	
	Ability to develop models that incorporate supply chain impacts, impacts of regulation and certification, and valuation of natural capital that underpins the food system and ecosystem services.	
	Delivery of interoperable data across data types and scales.	

Science, research and/or innovation challenge	Potential capability required	
	Capability to address the challenge	**UK capability required**
7. New energy systems, including decarbonisation: future energy systems are likely to incorporate a mixture of approaches and pathways including renewable and non-renewable energy. This will need better quantification of the resilience of renewable energy sources related to weather, marine and climate variability and change, as well as other systems potential impacts on the natural environment; likewise, bridging technologies such as Carbon Capture and Storage will need to be assessed.	Sustained observations of energy systems, including carbon capture and storage and geothermal. Observations of impacts on the environment.	
	Ability to model energy systems including whole life-cycles of generation, from installation, transport and operation, to decommissioning.	
	Delivery of interoperable data across data types and scales.	**Data infrastructure and HPC capability.** Increased capacity (computing power and storage), open data and open software, big data handling and skills, data assimilation, application specific design and the application of quantum computing are all required. Improved data access/assimilation/simulation etc. will help optimise the placement of sensor deployments. This underpins observations and simulations, but is particularly relevant for the environment sector due to the need to integrate data from distributed systems/data interoperability issues and to take a whole systems approach to addressing environmental challenges.
8. Water resources: improved integrated hydrological systems, including precipitation, and with embedding environmental exposure to water bodies, and human exposure through water supply, in our understanding of water resilience.	Sustained observations of hydrological systems.	
	Ability to model whole systems including impacts on human exposure.	
	Delivery of interoperable data across data types and scales, including with health data.	

Key Observations | Simulation | Data/data infrastructure

Science, research and/or innovation challenge	Potential capability required	
	Capability to address the challenge	UK capability required
9. Clean growth/ circular economy: e.g. resource recovery from waste/plastics.	Ability to monitor environmental impacts of economic activities, providing the environmental observations required to inform the life-cycle assessment for different waste treatments/resource recovery technologies.	
	Need the capacity to model complex, overlapping and inter-related systems (natural and anthropogenic processes) over the timescales that enable a view on the circular economy.	
	Delivery of interoperable data across data types and scales.	
10. Chemicals in the environment: pollution is the largest environmental cause of disease and death in the world today, responsible for an estimated 9 million premature deaths (Lancet Commission on Pollution and Health).	Observations of exposure routes, including through air, soil, water and food supply. Observations of the discharge of emerging contaminants (e.g. pharmaceutical compounds) through domestic, industrial and medical wastewater to freshwater environments, or to land, including agricultural land and food supply chain through grey water irrigation and resource recovery from organic waste streams.	
	Innovative infrastructures that integrate observations and modelling to deliver appropriate mitigation measures will lead to effective regulation and management of pollutants.	
	Delivery of interoperable data across data types and scales.	

Key Observations Simulation Data/data infrastructure

7.4 E-infrastructure needs

Many advances in environmental science are currently too computationally and/or data demanding to turn into operational services. Environment-specific challenges are largely centred around observations, modelling, simulation and prediction and the links between them. This often requires distributed infrastructures, including at the international level, alongside an increasing need to handle large, interoperable datasets and the challenges therein (such as quality control, common standards and the needs for new technologies in data science to translate data into useable information). In addition to the cross-sector e-infrastructure requirements outlined in chapter 9, the modelling, simulation and prediction requirements that are specific to the environment sector include:

- Labs or testbeds to pilot real-time forecasting underpinned by:
    - Observing systems
    - Simulations for scenario testing
    - Higher resolution data and models
    - Improved interoperability, measures and models
    - Better understanding of marginal risks and how they sum to major risk
- Simulation across systems, e.g. to identify the investment required to allow risk mitigation
- Formal assessment of probabilities, and hence risk, using ensemble techniques and the propagation of uncertainty down the value chain
- A whole systems approach, which will require increasing complexity of models (both in terms of resolution and the number of components of the earth system), and the requirements for modularity and open source software
- Redevelopment of environmental and Earth system models now to make optimal use of the next generation supercomputers and safeguard continued scientific advancement
- Investment in supercomputers and associated data processing platforms (such as JASMIN, a 'super-data-cluster' which delivers infrastructure for data analysis)
- Exploration of alternative techniques to augment high-end physical modelling of complex systems, rather than solely spending more on CPU and bigger models
- A national repository of environmental model code, which would preserve knowledge beyond a particular generation of hardware/software
- The environmental science community needs to draw on the very significant investments in data science in HEIs to turn this towards addressing environmental challenges

Chapter 8: Energy sector

This chapter describes the emerging themes within the Energy sector, spanning energy systems and technologies that are relevant to the Energy sector such as robotics, remote monitoring and control. Achieving clean growth – growing UK income while cutting greenhouse gas emissions – and an affordable energy support is at the heart of the Clean Growth Strategy and Industrial Strategy[83].

The UK was one of the first countries to recognise and act on the threat of climate change passing the Climate Change Act in 2008. We have been among the most successful countries in the developed world in growing our economy while reducing emissions. This has been aided by the falling costs of many low carbon technologies and technological innovation has driven development of a high-growth and high-value 'low carbon' sector in the UK.

The Industrial Strategy and Clean Growth Grand Challenge is an invitation to business, academia and civil society to work together to innovate, develop and deliver clean energy technologies and industries of strategic importance to our country. 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[83]. Action to deliver clean growth also has wider benefits, for example, cutting transport emissions leads to cleaner air and positive impacts on public health.

Achieving carbon reduction targets and transitioning to a low carbon economy is challenging. It means working across multiple energy technologies to address significant research and development challenges now, as well as developing the capability to support future innovations. Energy is a broad sector that covers several sub-areas including power systems, carbon capture and storage, energy storage, renewable and low carbon energy sources (nuclear, wind, marine, wave, tidal, solar and geothermal), alternative fuels, hydrogen, oil and gas, gas turbines, demand (from buildings, transport and industry) and energy models. In addition, this requires an understanding of the environmental impact of energy generation, and transmission, policy and societal implications. Many research and innovation challenges are multidisciplinary, for example bringing together electrochemistry, materials science, systems engineering and advanced manufacturing to develop low cost, sustainable and reliable energy storage.

The major public sector funders for energy research in the UK are BEIS and UKRI. Several UKRI councils support research and innovation programmes in energy, predominantly EPSRC but also ESRC, BBSRC, NERC, STFC and Innovate UK. EPSRC commissioned the Centre for Energy Systems Integration (CESI) to develop this forward view of the sector drawing upon a range of inputs including advice from interviews, expert consultation workshops and key reviews. The Energy Innovation Board[84] is undertaking a refresh of the Technology Innovation Needs Assessments (TINAs)[85], now referred to as Energy Innovation Needs Assessments (EINAs). The EINAs will report against all of the energy R&D technology areas in late 2019 and the final roadmap will need to both inform and be responsive to this assessment process.

8.1 Definitions and scope

Drawing on the findings from our interviews, workshops and key reviews, we have refined the programme-wide definition of research and innovation infrastructures to consider:

- Whole energy systems, including demand and networks
- Energy storage
- Renewable energy sources
- Carbon capture and storage
- Fuel cells and hydrogen
- Alternative fuels
- Nuclear energy

8.2 Understanding the landscape

Given the more focused topic area, the Energy sector consists of a relatively small group of infrastructures. However, energy research is multi and interdisciplinary in nature and a significant number of infrastructures within the PS&E sector, environment sector and e-infrastructure and data sector provide necessary fundamental science and address broader challenges linked to energy issues. As well as the core engineering and physical science requirements, this sector requires an understanding of how the macro level energy system functions and is used.

Energy is an entirely regulated sector. The wider policy and social context is also critical. Almost no energy generation technologies can be installed without either certification of the technology (nuclear) and/or permissions for installation (offshore renewables). This means energy technologies need to be thoroughly understood before they are allowed to market, leading to requirements for technology development, testing and certification capability.

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. The offshore renewable industry increased its installed capacity to over 12GW in 2018 from almost nothing in 2008. This rapid increase was made possible by the 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 Energy sector covers R&D from underpinning science to development and deployment. Most 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 (e.g. CCS) there are parts of the sector that require government support for higher TRL activity to prove and derisk the technology.
Overall, the UK has a good breadth of infrastructure capability. From the UKRI survey returns and from the interviews and workshops, it was found that there remain areas where additional infrastructure investment could be made that would help underpin certain core energy technologies. There is good collaboration between existing facilities; however, much could be achieved through support to better join these existing facilities to create distributed national capability rather than duplicating this capability in new single-site centres. A significant number of infrastructures from the PS&E sector, environment sector and e-infrastructure and data sector note Energy as an important sector they support.

Remote Applications in Challenging Environments (RACE) Centre

The RACE centre performs R&D into how to carry out tasks in hazardous and extreme environments, environments where people cannot work because conditions make it impossible or unacceptable. These conditions are found in nuclear power plants, petrochemical facilities, space exploration, construction and mining. The technical challenges to overcome include high radiation, extreme temperatures, limited access and operation in vacuum or extreme magnetic fields. The centre is funded by the UKAEA based at the Culham campus in Oxfordshire.

8.3 Key messages and emerging themes

Through the stakeholder and community discussions to help develop this chapter, the following key messages have emerged:

- 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 (NREL) in the USA. Many of the challenges described here also require **large demonstrators of multi-vector energy systems**, following the example of the Integrated Transport Electricity Gas Research Laboratory (InTEGReL), and including capabilities for multi-disciplinary research and innovation. Creating these larger scale activities are particularly important in the Energy sector because the problems are inherently multi and interdisciplinary and, the potential for step change lies in the integration of individual research areas into the overall energy system. They can 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 more abundant ones, improved efficiency of manufacturing processes and end of life management of energy technologies.
- There is a 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, in order for the UK to benefit more from establishment of these facilities/laboratories/demonstrators. These facilities could enable the Energy sector to overcome challenges associated with operation, management and product development, as well as challenges associated with resilience and reliability of the energy system.
- In addition to the drivers for change discussed in chapter 2, energy infrastructures are particularly impacted by the scale and pace of transition to a low carbon energy system. This requires new and different types of research projects and associated infrastructures. New collaborative projects may require expansion of the capability of, and linkages between, large-scale facilities and it is likely the number of UK users who require access to infrastructures will increase.

The following tables summarise the emerging themes within the energy sector. Much of the underpinning research infrastructure requirements are captured in other chapters, particularly physical sciences and engineering. This chapter focuses more on particular requirements of energy research and innovation. For each theme, we present information on the specific and generic challenges associated with it and the infrastructure capabilities that may address those challenges.

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

A key tool for decarbonising energy is a better understanding of multi-vector energy systems – such as electrical power, natural gas, hydrogen and heat – and how they can best be integrated. Achieving this requires 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.

Theme 1: Whole energy systems (including demand and networks)	
Science, research and innovation challenge	**Potential capability required**
Modelling whole energy system (energy focused), to understand the physical and cyber implications of decarbonisation of the power, heat and transport.	A Centre of Excellence for Energy Modelling to act as a custodian for nationally-important models. Interdisciplinary research facilities and labs that integrate the cyber and physical elements of a multi-vector energy system.
Optimising whole system control, investment, architecture and cross vector interaction.	Living lab demonstrators coupled with pipeline of innovation, data capture and analysis, market development, and considering the socio-techno-economic impact.
Digital Twins (sensor-enabled digital replica of physical system) of whole energy system.	Cyber-physical demonstrators for energy systems, including sensors, high performance computing, and cyber-physical model of energy system.
Decarbonisation of heat (thermal comfort).	Flexible demonstrators for distribution networks to develop the three main heat options (electrification, repurpose for hydrogen and district heating).

Theme 2: Fuel cells and hydrogen

Hydrogen is considered a promising pathway to enable a low carbon economy, since hydrogen can be used in heating, transportation and power applications (particularly with fuel cell technologies). Hydrogen can directly replace methane in gas networks with less impact on the public. Hydrogen storage is also possible on a seasonal scale. This enables surplus renewable energy generated in the summer to be used for hydrogen generation, which can be stored until winter when demand is higher than generation. Such inter-seasonal storage is more difficult and expensive to implement with batteries.

Fuel cells are essential technologies within the hydrogen energy pathway. The challenges for fuel cells research include improvement of performance, reliability, robustness and cost of this technology by 2025-2030.

Theme 2: Fuel cells and hydrogen	
Science, research and innovation challenge	**Potential capability required**
Hydrogen use and safety of devices.	Hydrogen utilisation centre of excellence supported by manufacturers with accompanying networks to develop and share knowledge.
Bulk production of low carbon, low cost, resilient hydrogen.	One or more low carbon hydrogen production demonstrators that can demonstrate that hydrogen can be produced and supplied to the commercial market at a competitive cost.
Use of hydrogen in the gas grid, as an admixture or as 100% hydrogen.	R&D and demonstration in re-purposing gas infrastructure (TRL 5-8), combustion (TRL 6-8), fuel cell research (TRL 6-8) and gas storage (TRL 3-6).
Understanding and addressing challenges associated with underground storage of hydrogen.	Facilities or a laboratory with an array of boreholes, as well as hydrogen storage, pipework and measurement equipment.
Improvement of performance and reduction of the cost of fuel cells.	An R&D facility focusing on R&D of the hydrogen economy and development of fuel cells technology.

Theme 3: Energy storage

Energy storage is an important technology to support matching of supply and demand. It is often described as an enabling technology for renewable energy in particular as it enables storage of surplus renewable energy at times of insufficient/low demand. Energy storage therefore increases flexibility of energy systems. Further research is needed into the technical flexibility of storage and associated costs (whilst noting that the static vs mobile energy storage applications have different research needs).

Theme 3: Energy storage	
Science, research and innovation challenge	**Potential capability required**
Developing low-cost energy storage for electrical energy and thermal (heat/cooling) demand at large scale.	Demonstrators are needed to allow different energy storage technologies to be scaled-up and tested, across different applications: e.g. domestic, grid-scale, generation-integrated, in distribution networks, neighbourhood scale.
Flexibility of storage in living lab conditions.	Living labs of scale in different archetypes (urban, sub-urban, mixed, industrial) Facility for the study of social aspects of energy storage especially large consumer studies and change studies.
Integrating energy storage with wind energy generation.	A wind turbine test facility where 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.	Synthesis, characterisation and testing facilities for advanced materials.

Theme 4: Renewable energy sources

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

Theme 4: Renewable energy sources	
Science, research and innovation challenge	**Potential capability required**
Social and environmental research in printed Photovoltaics (PVs), support to scale up and commercial interest.	A national centre for low cost printed PV to support the distributed research community in the UK and bridging the void towards manufacturing and adoption.
Understanding of large-scale tidal stream/wind/wave energy extraction and its interaction with the environment.	Large laboratory scale wind-wave-current combined basins and measurement systems (fully instrumented at-sea demonstration sites).
Development of UK geothermal potential. The new UK Geoenergy Observatories (UKGEOS) facility will make significant contributions to underpinning subsurface geothermal science, as well as to other energy areas. However, additional capability in this area will be needed as the area grows in national importance especially if the technology moves to the development stage.	A medium- to large-scale demonstrator, to carry out fundamental research on geothermal energy co-production, possibly coupled with oil and gas production.
To address operational issues associated with reduction of the inertia of the energy system due to high penetration of renewables.	A facility with asynchronous inertia shafts, such as those found in wind turbines, for testing approaches to add inertia to the electricity system.

The Offshore Renewable Energy (ORE) Catapult

The Offshore Renewable Energy Catapult includes the world-leading 100m blade-test facility in Blyth, Northumberland. The facility's work includes testing one of the world's longest offshore wind turbine blades, the 88.4m LM Wind Power blade, which has been developed as part of XL-Blade, an EU Demowind-funded project that aims to reduce the cost of offshore wind by designing, validating and deploying the world's largest offshore wind turbine blade.

ORE Catapult

Theme 5: Alternative fuels

Reduction of greenhouse gas emissions of the transport sectors, including the road, rail, aviation and shipping sectors, can be achieved by using low carbon liquid fuels, e.g. bioenergy value chain, biofuels as well as electrification (dependent on range required) and hydrogen (see theme 2). Alternative fuels such as biofuels, which help reduce reliance on fossil fuels, can be produced from agricultural (residue) and non-agricultural (algae) sources.

Theme 5: Alternative fuels	
Science, research and innovation challenge	**Potential capability required**
All the parts of the value chain for biofuels Advance mapping of the relationship between fuel chemistry and its characterisation properties including pollutant emissions	A multidisciplinary lab in alternative fuels to cover chemistry, agriculture, and mechanical engineering Academic facilities (virtual) linked together through a central facility
Zero emissions vehicles other than cars (e.g. large vehicles, non-automotive sectors such as diesel generators, aviation or marine)	A central, co-ordinated hub to identify and strategise the options for alternative fuels. Growing out of this, a centre of research in a similar remit to the Faraday Institution to enable the alternatives to be fully researched and delivered
Mapping of organic waste availability and evidenced based Life Cycle Analysis work to look at the environmental impact of existing systems versus the potential savings of using Anaerobic Digestion (AD)/ biorefineries in urban/agricultural contexts	A 'virtual centre for AD' with a cooperative (rather than competitive) programme of research including academia and industry
Combustion and conversion	Fundamental experimental equipment that is heavily instrumented to provide the controlled environments needed to better understand biofuel combustion behaviour and its effects on the internal combustion engine

Theme 6: Nuclear energy

Nuclear energy includes both nuclear fission and fusion. Nuclear fission is recognised by the UK government as having an important role in achieving clean growth. UK energy security and planned expansion of nuclear is a key part of the future energy mix, essential to meeting emission targets and achieve decarbonisation of the energy network[11,86,87]. The challenge is to deliver the next generation nuclear (including Gen(III)+, SMR and AMR) and design and deploy energy systems that can deliver flexible heat and power. Nuclear also has a substantial legacy, and effective management is essential. Nuclear fusion is also likely to play a role from 2050 onwards and research undertaken today will be critical in delivering this longer-term goal.

There are many complementary research and innovation challenges across both fission and fusion research, such as robotics (e.g. removing human intervention), remote monitoring and materials science. Other important challenges include the development and manufacturing of future fuels building on the existing UK capability, minimising and managing waste, plant decommissioning, regulation, public acceptability, plant design and operation, reducing the cost of new build, developing advanced reactor technology, the fuel cycle, environmental impact and geological waste disposal. Information on future research requirements has been published by the Nuclear Innovation Research and Advisory Board (NIRAB)[88]. Finally, there are significant opportunities to work across nuclear and social research to understand the social implications of nuclear energy and how we could deliver a transformative shift to clean growth.

Theme 6: Nuclear energy	
Science, research and innovation challenge	**Potential capability required**
Develop the nuclear engineering capability needed to support any future new build programme, especially in system engineering.	Nuclear energy centre or centres of excellence are needed, to enable multi-disciplinary nuclear energy engineering through shared scientific facilities. Demonstration sites are needed to support the work of the Catapults.
Management of the nuclear legacy (low-, intermediate- and high-level waste, decommissioning technology, and nuclear logistics).	Facilities and access for handling/analysing active materials, better engineering and scale up. Facilities to design and develop waste minimisation, treatment and management technologies in both active and non-active environments. Facilities to draw on massive advances in retail logistics through using the distributed digital system such as distributed control system for nuclear power plants which can improve the performance of the system by using advanced Human System Interface, bus technology, enhanced diagnostics and maintenance.
Fission: Future Fuels Requirements of future nuclear reactors (GenIII+, Gen IV, AMRs, SMRs etc.).	Facilities to develop and test the fuels of the future, including accident tolerant fuels. Maintaining and growing UK advanced fuel capability that will be needed for existing and future reactors, both civil and defence.
Fusion: Plasma control (superconducting magnets, machine geometry and heat management).	Large fusion reactor(s) to support research into plasma control and fusion and superconducting magnet technology is required. Demonstration facility for a spherical tokamak capable of producing electricity.

Theme 6 cont.	
Science, research and innovation challenge	**Potential capability required**
Enable high heat extraction, robotic maintenance and health monitoring of nuclear reactors.	Comprehensive conceptual design centres to address high heat flux, robotic maintenance, component testing and material research for nuclear energy.
Improved thermal transfer from reactor to electricity generation systems.	A thermal hydraulic research and test facility
Advanced reactor understanding and development.	Facilities that underpin the design capability understanding in the UK, to enable the informed assessment and development of future reactor designs, their regulation and operation.
The UK has many nuclear plants that are being, or are due to be, decommissioned. The safe long-term storage and disposal of spent nuclear fuel and waste from decommissioned nuclear plants, and the clean-up of old nuclear plant sites, is a significant issue for the sector.	A facility for the assessment of containment technology, geo-barriers and host rock properties/interactions with the stored waste. A facility for environmental remediation.

Theme 7: Carbon capture and storage (CCS)

CCS, along with its parallel research area carbon capture utilisation and storage (CCUS), 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 the methane, and the hydrogen can then be used as a clean energy vector. These technologies could be applied to mitigate between 15% to 80% of current world carbon emissions and the UK is uniquely placed with potential offshore storage for CO_2.

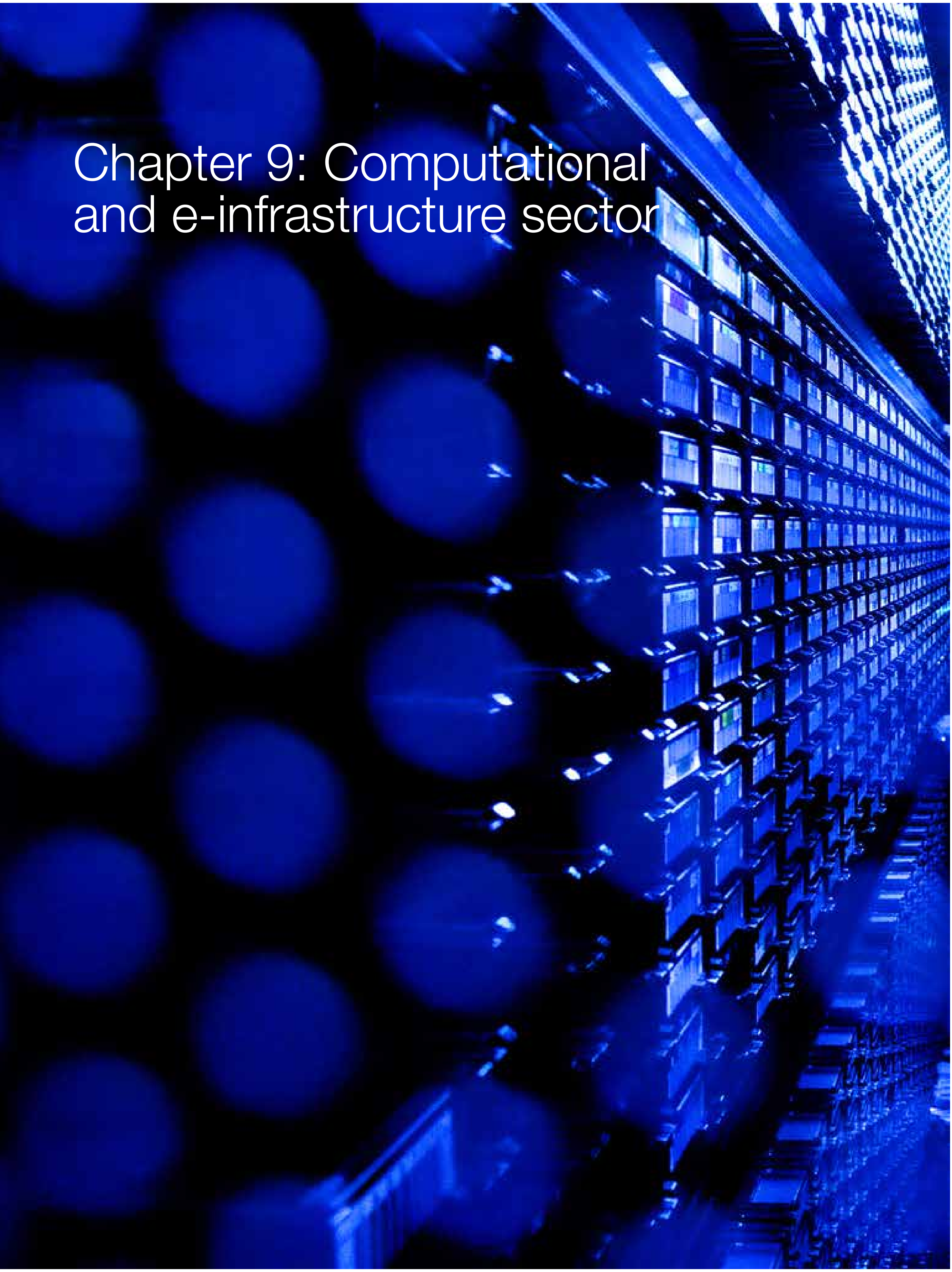
Theme 7: Carbon capture and storage (CCS)	
Science, research and innovation challenge	**Potential capability required**
How the CCS infrastructure integrates with the wider energy system	Demonstrators to show how CCUS copes with demand variation using component testing across the CCS chain, a CO_2 storage pilot site, a combustion/hydrogen production pilot scale facility, and a CO_2 transport facility
How to decarbonise heavy industry with Carbon Capture, Utilisation and Storage (CCUS)	A network of coordinated facilities for demonstrating next generation capture and utilisation technologies, as well as optimising amine scrubbing, at a scale of 1-10 MWe equivalent. This would act as an essential bridge from small pilot plants to full-scale demonstrators. At a smaller scale, this network should also cover emerging next generation capture technologies which can be developed through pilot-plants operating at a scale of ca. 50-500 kWe
Understand low carbon generation with CCUS	Pilot scale facilities to bridge the gap between fundamental research and commercialisation (TRL3-6)
Study CO_2 within the storage facility, and reaction of CO_2 with the host rock and the underground biology	A demonstration facility with CCS as part of an integrated energy system. There is a need for a "borehole Lab", with an array of boreholes, instrumentation and research capability

8.4 E-infrastructure and data

There is a strong need for e-infrastructure in the Energy sector including data collection and processing, storage, accessibility, reliability, security, analysis and supporting skills. E-infrastructure supports research and innovation into operational challenges and system resilience. It can enable the identification of vulnerabilities in the cyber and physical infrastructure of the energy system and mitigate identified 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, product development, support standardisation and improve system management and operation. In addition to the cross-sector e-infrastructure requirements outlined in chapter 9, the facilities and capability that are required to address challenges in the Energy sector include:

- Open access national databases of technical data, demographic data, behavioural data for the Energy sector and 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
- A national coordination centre that will provide access to infrastructure and an open access data platform (e.g. ERIGrid that connects European Smart Grid Infrastructure). This will enable communication between the various facilities that already exist. The facilities brought together by this coordination centre would enable testing and validation of the concepts developed in the Energy sector.

Chapter 9: Computational and e-infrastructure sector



STFC \ Alan Ford

This chapter describes the emerging themes within the computational and e-infrastructure sector. E-infrastructure has grown from being the domain of specialists to an essential and pervasive infrastructure that supports key research and innovation challenges across the whole UKRI domain. It increasingly underpins much of the work of the other sectors discussed within this report and will be vital to maintaining the UK's strengths in research and innovation. Without effective e-infrastructure, the value and efficiency of other infrastructures is reduced.

The 2018 Blackett Review[89] stated "Computational modelling is essential to our future productivity and competitiveness, for businesses of all sizes and across all sectors of the economy". Realising these benefits requires rapid routes to market supported by a national e-infrastructure that simplifies and encourages two-way collaborations between industry and academia. Our vision is that by 2030, the UK's e-infrastructure will be integrated in such a way that any eligible and appropriately authorised researcher in the UK is able to access any data, computational or experimental system or other resource in a straightforward, secure and consistent way that removes present barriers to access.

EPSRC, STFC and NERC are the major councils within UKRI that fund supercomputing, as their communities are currently the greatest source of demand and the majority of users. Supercomputing is also central to the Met Office's operations and R&D efforts. All of the UKRI councils fund elements of e-infrastructure associated with data storage and analysis. Jisc, the UK higher, further education and skills sectors' not-for-profit organisation for digital services, is responsible for the Janet network and a range of other digital resources and infrastructures such as identity management and information security.

To develop the themes within this chapter we have drawn upon a range of inputs including expert workshops and a number of earlier independent strategic reviews and recommendations, including the work of the RCUK e-infrastructure Project Directors Group.

9.1 Definitions and scope

For the purposes of the roadmap programme we have defined e-infrastructure as all infrastructure that enables digital/computational research. E-infrastructure should be regarded as 'scientific instrumentation' and can include:

- The facilities providing e-infrastructure
- Experimental facilities, with a major requirement for e-infrastructure to support the research that facility users are carrying out

Building blocks of e-infrastructure	
Networks	• International/national (GÉANT and Janet), local networks
Software	• Tools (operating systems, digital and software libraries, access management systems etc.) • Application codes (modelling, simulation and data analytics)
Computers	• A tiered approach to provide a diversity of computer systems configured for modelling, simulation and high-throughput data analysis
Data storage	• Short-term and archival storage/preservation
Access mechanisms	• Cloud technologies • Access management and identity management technologies

- Data facilities and resources, with a major requirement for e-infrastructure to support the research that facility users are carrying out
- Research centres/institutes that may have their own e-infrastructure to support research programmes, but which may require access to the three other classes of e-infrastructure above

Data resources have not been included in this chapter having already been discussed throughout the previous sector chapters. However, the infrastructure for moving, storing, analysing, visualising and archiving data is included here.

9.2 Understanding the landscape

The **demand for access to e-infrastructure and increased capacity continues to grow**. The way research and innovation is carried out has changed, making a strong e-infrastructure an essential capability to the majority of disciplines. We have already seen an exponential growth in the use of computational approaches over the last five to ten years and this is projected to increase. Chapter 3 has already described the increased digitisation of research and expansion into new fields such as SSAH. This increasing volume and complexity of data places additional requirements on e-infrastructure systems. The need for data analytics is increasing with many of the challenges described in this report requiring the merger of data sets to explore new questions (see table below). Theory research in most fields is now synonymous with computational research.

The diversity of users and research problems brings a requirement for **diversity and heterogeneity in e-infrastructure systems.** A wide range of different e-infrastructure is currently in use, both generic and optimised for specialised tasks alongside a range of local, regional, national and international provision.

A significant majority of research, across all disciplines, relies on **specialist research software**. Research results can only be relied upon if the techniques are reproducible and the software is high quality. This software represents a significant investment and

Research drivers and e-infrastructure

	Biological sciences, health and food	**Environment**	**Energy**	**Physical sciences and engineering**	**Social sciences, arts and humanities**
Modelling and simulation, requiring supercomputing	✓	✓	✓	✓	Currently small amounts
Experimental and observational data, requiring analysis, storage and networking	✓	✓	✓	✓	
Cohort and longitudinal studies, requiring long-term archives	✓	✓			✓
Sensitive and confidential data, requiring governance and access management	✓		✓ Commercial data	✓ Commercial data	✓ Sensitive, confidential and commercial data
Digitisation of collections, requiring storage and data management tools	✓				✓

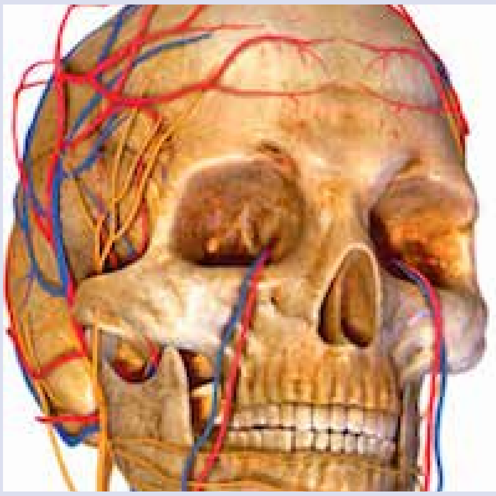
encapsulates valuable knowledge. It is a research output in its own right and forms a key part of the research and innovation infrastructure.

High-performance networks, i.e. those combining high bandwidth capacities, low end-to-end latencies and high reliability, are the basis upon which any e-infrastructure is built. The initial analysis describes the current UK research e-infrastructure landscape.

There are three building blocks: Janet (the UK's Research and Education Network), the various university and research institute campus networks which it interconnects and the GÉANT network through which Janet delivers global reach. Janet is managed on a five year rolling forward-look basis. This has over the last three decades ensured that each university and research institute has received national and international network capacity and reliability sufficient to business and mission needs.

Improving neurosurgery through HPC and novel software

UCL 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.



The underlying hardware changes rapidly, with major refreshes needed on a timescale of three to five years as part of planned, strategically managed investment. Timely investment in e-infrastructure is necessary to support research and innovation across the landscape. This is a critical interdependency for other research and innovation investments. For example, without adequate e-infrastructure researchers will not be able to analyse the data and run associated simulations described in earlier chapters. Over the last decade cloud computing has brought about a fundamental shift across many sectors in the way IT infrastructure is provisioned and accessed. Cloud is a technology and a service model. It can be delivered in many ways, including on-premise (private cloud), via commercial companies such as Amazon (public cloud), or via a collaborative e-infrastructure investment in shared resources (community cloud).

9.3 Key messages and emerging future directions

The changing nature and demands from research and innovation communities have particular implications for e-infrastructure systems.

- **Computational requirements** of models are increasing due to:
    - o Increased resolution: running models based on existing understanding but at finer scales
    - o Increased complexity: introducing new processes into models to reflect progress in theoretical understanding, often needed to match resolution increases
    - o Coupling of models: multi-physics, multi-scale modelling; the ultimate goal is real-time, 'whole system modelling'
    - o Quantification of modelling uncertainty using large ensembles of simulations to provide robust statistics

This leads to an ongoing demand for more supercomputing capacity and capability.

- Direct numerical simulation and modelling is increasingly a core activity across all disciplines. This implies significant growth in new fields adopting supercomputing approaches (e.g. deep learning on social science data sets).
- There is a growing requirement for simulations and modelling concurrent with experiments or observations where models evolve in line with data acquired. Experimental/observational facilities therefore need access to local Tier 2 computing capabilities as well as the option to burst out to the Tier 1 or Tier 0 national supercomputing facilities.
- Data analytics increasingly depend on more sophisticated algorithms as data volume, variety and complexity all increase towards exascale. We are already seeing the beginning of a convergence of HPC and supercomputing approaches to manage this, including the development of data-intensive approaches.
- How can **cloud computing** be fully integrated into the diverse range of research activities to enable future productivity? The public cloud may not be able to support some classes of research and innovation problems (e.g. leading-edge supercomputing) so a mixed model of on-premise and commercial cloud would allow us to use the strengths of both approaches (see figure 6).

- **Data infrastructure:** there are multiple strategic challenges to address data access/analysis/storage/archive/curation issues as the scale and capacity required grow (see chapter 3.6). A tiered approach to data infrastructure is needed to reflect a wide range of access requirements (volume, frequency, proximity to compute) and/or restrictions. Enhanced data movement tools (between tiers and around network) and skilled people to support them are vital. Horizon scanning is also essential to keep abreast of technology developments as new options for data hierarchy emerge (e.g. SSD). Future

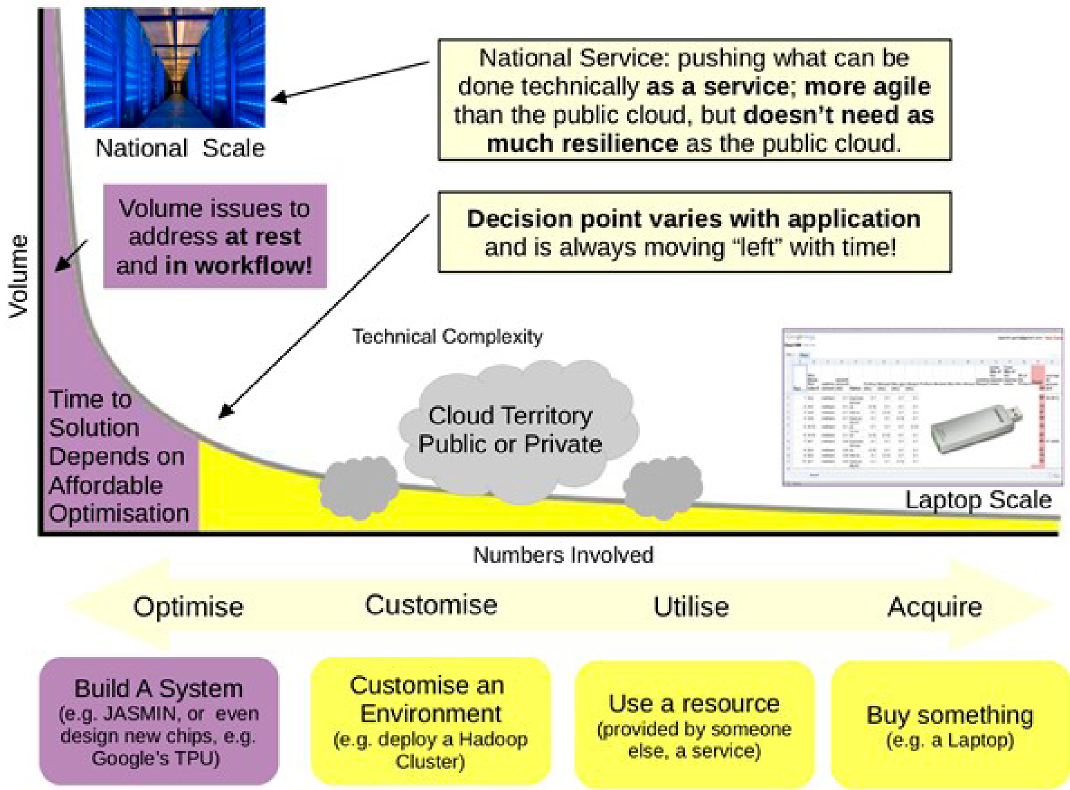


Figure 6. Cloud versus on-premise (credit: Bryan Lawrence).

increases in network bandwidth will need to be delivered consistently, to take into account the requirements thrown up by increased data production.

- **Information governance and security:** as described in chapter 3 the ability to interrogate new, large data sets bring governance and security challenges. This requires the development of new appropriate software environments and access management mechanisms to allow the secure handling of confidential data such as medical data. Robust information governance within the UK's e-infrastructure is of critical importance. As innovative uses of data, including the rapid development of AI and its associated ethics, permeate research and innovation activity, appropriate information governance needs to remain at the forefront of e-infrastructure community activity.
- **Research software** typically has a lifetime measured in decades and investment needs to be driven by a solid understanding of its lifecycle. This includes support for the work required to take it from exploratory research code to a widely-exploited tool that evolves to include new knowledge and be used in new contexts.
- The Industrial Strategy highlights the transformational potential of the new generation of algorithms often described as AI. This progress in algorithms is realised in code so good scientific software underpins the current revolution in machine learning and will enable all similar new advances in the future. This has implications for the provision of the right sort of e-infrastructure: software tools and hardware.
- **Access mechanisms:** to reach the vision of integrated access for researchers and innovators to the UK's e-infrastructure investment will need to be made into governance, standards, operating models and identity management/access management infrastructure.

pasja1000 on Pixabay

Using novel software to improve wind turbine design

Understanding the energy yield of wind turbines requires an understanding of the wind flow past the blades and the loading that can occur on the material. New wind turbine designs make use of moveable wings which complicates the required modelling. EPSRC funded researchers from Lancaster University developed novel software to model these complex wind turbines. They used the N8 regional HPC centre to test and model features of the code speeding up the analysis and creation of new international collaborations.

The general requirement for skilled people has already been discussed in chapter 3. For the e-infrastructure sector in particular we need to ensure all researchers receive the most appropriate training for their needs. As research tools and techniques change some level of skill will be a basic requirement for most researchers as well as more specialist training and skills requirements (see figure 7). Career support is needed to allow people to use their computational expertise to advance research, both as part of a research career and in new expert roles such as research software engineers and data scientists. As systems become more complex to manage, the need for a new role, ResOps, is emerging (expertise in systems management and service design and delivery), alongside increased requirements for research software engineers and data scientists.

Processes need to be put in place to **enable industrial access to e-infrastructure** for pre-competitive and collaborative research, and for innovation. This will require access to technical and RSE support, particularly for SMEs. Maximising industrial awareness of what e-infrastructure is available will be key. The table opposite summarises the emerging themes from our work and engagement so far.

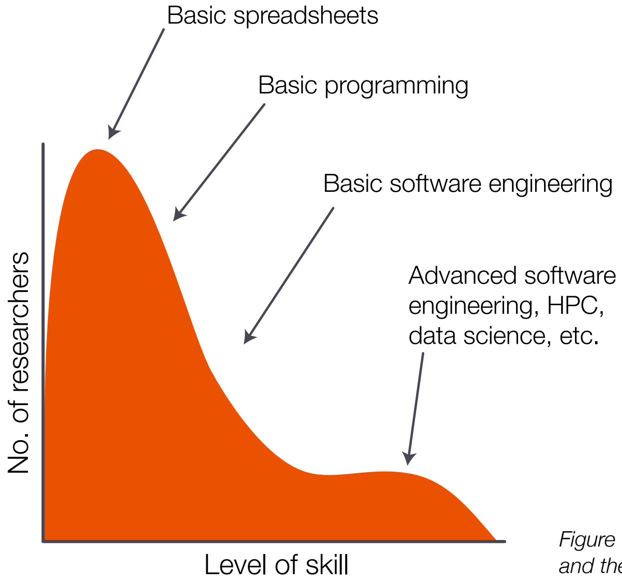


Figure 7. Indication of the e-infrastructure skills needs and the volume of researchers that need them.

Science, research and innovation challenge	Potential capability required
Computer hardware: • A tiered approach that supports the large and diverse user population • Underpins all areas of research • Ever-growing capacity needed • New technology opening up new capabilities	Continue to invest in Tier 2 computing: to build capacity at facilities and institutes, and regionally; to provide an architectural diversity.
	Continue to invest in Tier 1 national services, to reflect diverse needs of research communities.
	Exascale: consolidate science drivers into a single case; aim towards Tier 0 exascale by 2023/25.
	Establish co-design/technology foresighting programme, jointly funded with vendors, and involving mathematicians, computer scientists and computational researchers, to ensure UK can respond to new technological developments.

Science, research and innovation challenge	Potential capability required
Software: • Reliable high-quality software tools key to digital research • Needs long-term support while keeping up with hardware changes • New tools need to be developed in ML/AI domain	UKRI needs a software infrastructure strategy that reflects diversity of code base and centrality of the role of software in delivery of research and innovation. This would: • Support the recognition of software as a research output • Mandate planning and resource allocation for software development as part of UKRI grant application process • Provide long-term cross-UKRI support for software maintenance and development
	Establish a nationally coordinated and funded service that allows researchers in academia *and* industry to gain help from RSEs.
	Establish a national software engineering service to enable QA on software.
	Ongoing support for existing communities (such as CCPs, RSEs).
	AI and machine learning: establish a major programme to develop generally available tools from the discovery work that has been funded, as toolkits currently in use do not scale (e.g. single GPUs in desk-tops).
Data Infrastructure: To provide the necessary storage capacity and data management tools.	A working group has been established to develop a roadmap which encompasses data storage (from short-term to archives) and tools (access management, curation, meta-data etc.).
Network: To provide the high-performance network that is a key underpinning feature of e-infrastructure, taking into account capacity planning and technology developments	• Sustained funding for Janet on a five-year rolling forward look basis, with a major review around 2025 of future capital needs. • Continued participation and influence in GÉANT as the UK leaves the EU, through Horizon 2020 and Europe. • Development of standards, tools and skills to ensure that all universities and research institutes architect and maintain campus networks to take full advantage of Janet and GÉANT. • Funding flexibility to ensure that Janet and campus networks are adequately protected against cyberattack in an increasing variety of form and intensity.

Science, research and innovation challenge	Potential capability required
Security: To provide the necessary information governance practices, in recognition of the growing integration/merging of different data sources.	• Funding to maintain protection of all critical e-infrastructure. • Increased awareness of and provision of the tools and skills to counter the threat landscape to security of infrastructure, data and intellectual property among the research base. • Continued collaboration with the UK security services to maximise protection of UK assets.
Access mechanisms: To enable researchers to access the UK's e-infrastructure to support their research.	UKRI policy development to underpin migration of the UK research base to a national Authentication, Authorisation, Accounting and Identity Management (AAAI) system. To develop a reference architecture for a national AAAI that will support the first wave of integration. To support sustainable operation and development of a national AAAI.
Cloud: To develop a decision framework that allows providers to choose the optimal solution.	Formalise the Cloud Working Group and fund them to develop the policies, software and legal and economic frameworks that will enable the UK research community to take a leading role in the utilisation of cloud. Engage with public cloud providers to develop a policy and cost model that fits the research community's computing needs.
People: To ensure a cadre of trained people are available both to use and support/manage/run the infrastructure, but also to move into industry.	Improve provision of training at all career stages: undergraduate, Masters, PhD, postdoctoral, and Continuing Professional Development (CPD) (especially online training) Support an analysis of software training to identify materials and conduct gap analysis. Investigate mechanisms for sharing materials. Demonstrate the impact of software training, with the long-term aim of developing a visionary UK-wide training programme. Support an exchange programme with industry (e.g. secondments, sabbaticals) to encourage two-way exchange of ideas. Develop more meaningful and stronger links between domain science, computational science, computer science and maths to ensure knowledge is shared.

Chapter 10: Next steps

This progress report summarises our work to date. It draws on various sources including our questionnaires to existing infrastructures, consultation workshops with stakeholders (including other government departments and public sector research establishments) and the extensive advisory networks within UKRI. It is intended to stimulate and support further discussion.

As a new organisation, in 2019 UKRI will continue to engage with our stakeholders on a wide range of questions around how we fund research and innovation, and on how we can maximise the benefits of our investments, including in infrastructure, to help deliver the Industrial Strategy and shape the 2.4% roadmap.

The next step for the infrastructure roadmap programme will be to take the themes and issues identified here and develop them with continued input from the research and innovation community identifying any major themes not yet captured and opportunities for further connections across the landscape.

To facilitate this, we are continuing the consultation with our existing advisory networks alongside focused workshops and discussions with stakeholders both within individual sectors and considering the wider policy issues.

We will also draw on relevant parallel projects and reviews and the final data gathered through the questionnaires to infrastructures.

Further information about the programme can be found on the UKRI website (www.ukri.org/research/infrastructure) and feedback can be sent to infrastructure@ukri.org.

The final report will set out options for how the potential capabilities described in this report might be achieved. We plan to publish this first edition of the roadmap in summer 2019, with a view to reviewing and updating it every few years through a regular cycle of discussion with the research and innovation community.

As this is the first roadmapping exercise of this scale undertaken in the UK, there will also be lessons learned that we can build into future iterations. It will be possible to build on this initial work over time exploring key issues in more depth in future editions.

Acronyms

5GIC	5G Innovation Centre
AAAI	Authentication, Authorisation, Accounting and Identity Management
AD	Anaerobic Digestion
ADRP	Administrative Data for Research Partnership
AHRC	Arts and Humanities Research Council
AI	Artificial Intelligence
AIRTO	Association for Innovation, Research and Technology Organisations
AMR	Advanced Modular Reactors
APHA	Animal and Plant Health Agency
AR	Augmented Reality
ARCHER	Advanced Research Computing High End Resource
ARUK	Arthritis Research UK
ASTeC	Accelerator Science and Technology Centre
ATLAS	A Toroidal LHC Apparatus
BBSRC	Biotechnology and Biological Sciences Research Council
BEIS	Department for Business, Energy and Industrial Strategy
BES	British Election Study
BFI	British Film Institute
BHF	British Heart Foundation
BH&F	Biological Sciences, Health and Food
BIS	Department for Business, Innovation and Skills
BP	British Petroleum
BRI	Brewing Research International
BSL	Biosafety Level 3
CCP	Collaborative Computational Project
CCS	Carbon Capture and Storage
CCTV	Closed Circuit Television
CCUS	Carbon Capture, Utlisation and Storage
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CERN	Conseil Européen pour la Recherché Nucléaire (European Organization for Nuclear Research)
CESI	Centre for Energy Systems Integration
CLASS	Composite Lightweight Automotive Suspension System
CLF	Central Laser Facility
CLOSER	The Cohort and Longitudinal Studies Enhancement Resource
CLS	Centre for Longitudinal Studies
CMS	Compact Muon Solenoid
CO2	Carbon dioxide
CPD	Continuing Professional Development
CPU	Central Processing Unit
CRUK	Cancer Research UK
Cryo-EM	Cryo-Electron Microscopy
CT	Computerised Tomography
CVR	Centre for Virus Research
DCMS	Department for Digital, Culture, Media & Sport
DEFRA	Department for Environment Food and Rural Affairs
DFE NI	Department for the Economy of Northern Ireland
DFID	Department for International Development
DHSC	Department of Health and Social Care
DLS	Diamond Light Source Ltd
DSTL	Defence Science and Technology Laboratory
DWP	Department for Work and Pensions
EBS	Extremely Brilliant Source
EEG	Electroencephalography
EINA	Energy Innovation Needs Assessment
ELIXIR	European Life Science Infrastructure for Biological Information
ELSA	Ethical, Legal and Social Aspects
EMBL	European Molecular Biology Laboratory
EMBL-EBI	European Molecular Biology Laboratory - European Bioinformatics Institute
EMPHASIS	European Infrastructure for Multi-scale Plant Phenomics and Simulation
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESRC	Economic and Social Research Council
ESRF	European Synchrotron Radiation Facility
FAAM	Facility for Airborne Atmospheric Measurements
FAANG	Functional Annotation of Animal Genomes
FAIR	findable, accessible, interoperable and reusable
FAO	Food and Agriculture Organisation
FEL	Free Electron Laser
FERA	Food and Environment Research Agency
FWCI	Field Weighted Citation Impact
GDP	Gross Domestic Product
Gen III+	Generation Three Plus, Nuclear Reactor Technology
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSO	Group of Senior Officials
GVA	Gross Value Added
GW	Gravitational Wave

HEFCW	Higher Education Funding Council for Wales
HEI	Higher Education Institution
HESA	Higher Education Statistics Agency
HPC	High Performance Computing
IBISBA	Industrial Biotechnology Innovation and Synthetic Biology Accelerator
IBM	International Business Machines Corporation
ICM	Independent Communications and Marketing
IKC SynbiCITE	Innovation and Knowledge Centre for Synthetic Biology
ILL	Institut Laue-Langevin
INSTRUCT	Integrated Structural Biology Infrastructure
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRO	Independent Research Organisation
ISCF	Industry Strategy Challenge Fund
ISIS	ISIS Neutron and Muon Source
IT	Information Technology
LARIF	Large Animal Research and Imaging Facility
LHC	Large Hadron Collider
LMB	Laboratory of Molecular Biology
MEG	Magnetoencephalography
MRC	Medical Research Council
MRI	Magnetic Resonance Imaging
NCSC	National Cyber Security Centre
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
NHS	National Health Service
NIAB	National Institute of Agricultural Botany
NIHR	National Institute for Health Research
NIRAB Board	Nuclear Innovation Research and Advisory
NMR	Nuclear Magnetic Resonance
NNL	National Nuclear Laboratory
NPL	National Physical Laboratory
NREL	National Renewable Energy Laboratory
NRF	National Research Facilities
NSTF	National Satellite Test Facility
OAS	Oxfordshire Advanced Skills
OECD	Organisation for Economic Co-operation and Development
ONS	Office of National Statistics
PEC	Policy and Evidence Centre
PET	Positron Emission Tomography
PHE	Public Health England
PS&E	Physical Sciences and Engineering
PSRE	Public Sector Research Establishments
PV	Photovoltaics
QA	Quality Assurance
R&D	Research and Development
R&I	Research and Innovation
RACE	Remote Application in Challenging Environment
RAPID-WATCH	Rapid Climate Change Programme
RCaH	Research Complex at Harwell
RCUK	Research Councils UK
RFI	Rosalind Franklin Institute
RRI	Responsible Research and Innovation
RSE	Research Software Engineer
SES	The Skills and Employment Survey
SFC	Scottish Funding Council
SIA	Science and Innovation Audit
SKA	Square Kilometre Array
SME	Small and Medium-sized Enterprises
SMR	Small Modular Reactors
SSAH	Social Sciences, Arts and Humanities
SSD	Solid State Drive
STFC	Science and Technology Facilities Council
SuperSTEM	National Research Facility for Advanced Electron Microscopy
TINA	Technology Innovation Needs Assessments
TNS	Taylor Nelson Sofres
TRL	Technology readiness level
UAV	Unmanned Aerial Vehicle
UCB	Union Chimique Belge
UCL	University College London
UKAEA	UK Atomic Energy Authority
UKDS	UK Data Service
UKGEOS	UK Geoenergy Observatories
UKRI	UK Research and Innovation
UKRPIF	UK Research Partnership Investment Fund
UKSA	UK Space Agency
UN	United Nations
UV	Ultraviolet
WERS	Workplace Employee Relations Survey
WHO	World Health Organisation
WMG	Warwick Manufacturing Group
XFEL	X-ray Free Electron Laser

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