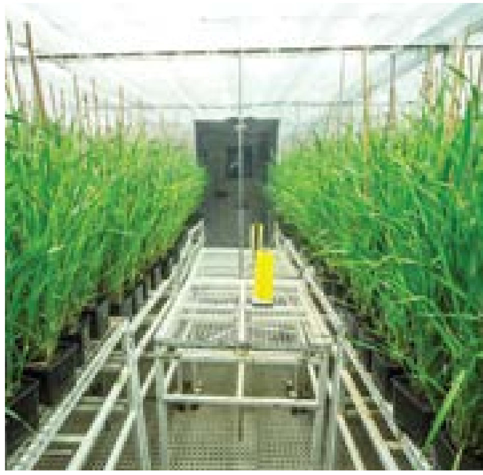
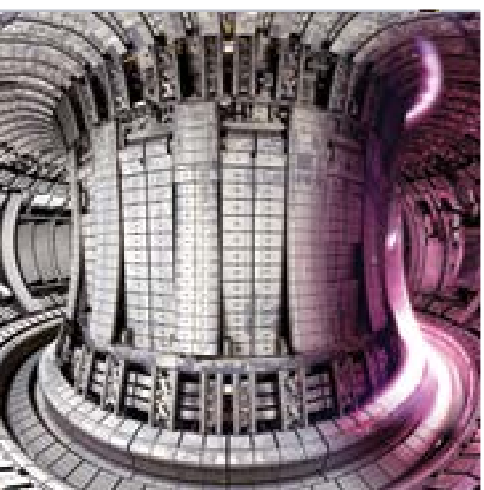
UK Research and Innovation

The UK's research and innovation infrastructure: Landscape Analysis



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UK's Research and Innovation Infrastructure
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Contents

Executive summary

Research and development (R&D) has a central role to play in driving economic growth. Meeting the ambitions of the Industrial Strategy, including delivering the four Grand Challenges and the target to increase total R&D investment to 2.4% of GDP by 2027, requires investment in infrastructure as the basis of our research and innovation landscape[1]. Today the UK is globally recognised as a leader in research and innovation, having the most productive science base in the G7 based on field-weighted citations impact and research papers produced per unit of R&D expenditure[2,3]. Every £1 spent on public R&D unlocks £1.40 of private R&D investment[4], together delivering £7 of net-economic benefit to the UK[5]. We are highly successful in translating knowledge into real-world societal, economic and international benefits. Estimates suggest that more than half of the UK's future productivity growth will be driven by the application of new ideas, research and technology to create new processes, products and services[6].

These successes are in large part founded on a network of internationally competitive, high-quality and accessible research and innovation infrastructures. The UK research and innovation infrastructure landscape is diverse, from large-scale physical research facilities such as synchrotrons, research ships and scientific satellites, to networks of imaging technologies and knowledge-based resources such as scientific, cultural or artistic collections, archives, clinical and population cohorts, data and computing systems. This report provides an overview of the current landscape using the broad sectors used by the European Strategy Forum on Research Infrastructures (ESFRI). It builds on the Initial Analysis[7] published in November 2018, filling in gaps in coverage and undertaking additional analysis to explore issues in more depth.

A snapshot of the UK landscape

Our questionnaire approach and analysis have identified over 750 infrastructures of regional, national and international significance, 527 of which are of national or international significance. Infrastructures are located in every region of the UK and around fifty are overseas in at least twenty-five different countries. Eighty-four per cent are housed within other institutions, primarily higher education institutions (HEIs). Some infrastructures, such as research ships, planes or satellites, have no fixed location. Others are distributed between multiple sites.

Infrastructures of all sizes require staff with highly specialised skills. The national and international infrastructures responding to our questionnaires employ just under 25,000 full-time equivalent staff (FTEs) in the UK. Infrastructures need a range of functions to operate, including research, technical and other roles (e.g. managerial, administrative). Five of the six sectors had more than three quarters of staff in research and technical roles. On average, functions are split as follows: 38% of staff in technical roles, 33% in research and 29% in other roles.

Collaboration with business and the wider economy

Over three quarters of infrastructures conduct some work with UK businesses, with 17% conducting most or all of their work in this way. At least fifteen infrastructures identified that they work with or contribute to every one of the forty economic sector groupings, indicating the breadth of these interactions. Across the landscape the most highly cited economic sector interactions outside of research and education were public policy, health services, energy utilities, instrumentation manufacture, agriculture, communications, computing and data services, pharmaceuticals, electronics manufacture and aeronautical transport.

Modern research and innovation is rarely single domain-led. Ninety-two per cent of infrastructures work across more than one research sector with the computational and e-infrastructure sector having the broadest reach. Some infrastructures are designed from their outset to be large-scale facilities serving multiple sectors with applications across the economy.

International collaboration

The Smith Review highlights the importance of international collaboration. Ninety-two per cent of infrastructures collaborate with international partners. They play an important role in the mobility of talent, acting as a magnet to attract leading researchers and innovators

Top three economic sectors cited	
Biological sciences, health & food	Health services, agriculture, pharmaceuticals
Physical sciences & engineering	Instrumentation and electronics manufacturing, energy utilities
Social sciences, arts & humanities	Creative industries, public policy and social services, communications
Environment	Public policy, energy utilities, agriculture
Energy	Energy utilities, instrumentation and general manufacturing
E-infrastructure	Computing, health services, communications

from across the world. Twenty-seven per cent of infrastructures' staff were from overseas with computational and e-infrastructure having the greatest reliance on non-UK nationals at 39%. Thirty-nine per cent of users of infrastructures also come from outside the UK. Often this is because there is no similar capability elsewhere, the infrastructure being integral to international collaboration and the quality of support on offer at UK infrastructures.

Long-term investments

Our data demonstrates the UK's long history in developing research and innovation infrastructures with substantial investment in new capability apparent over the last twenty years. The earliest infrastructures tended to be collections housed in museums, libraries or gardens. Social and political drivers led to the first agricultural and environmental infrastructures appearing early in the twentieth century. The 1950s, 1960s and 1970s saw the establishment of large infrastructures such as at Conseil Européen pour la Recherche Nucléaire (CERN) and the British Library. By the 1980s large computational and data infrastructures were more common and the 1990s through to the 2000s saw the diversity of the landscape continue to expand with a greater focus on innovation, imaging, autonomous systems, the 'omics' and quantum technologies.

Infrastructures are long-term investments and 60% have operational lifespans of over twenty-five years. Infrastructures in areas reliant on technology with rapid evolution rates, such as e-infrastructure, tend to have shorter lifespans. In other areas, such as data and collections, infrastructures increase in value over time. However, largely due to the uncertainty around funding cycles, only 41% of infrastructures felt they could plan over three years ahead and yet over three quarters of infrastructures are facing major decisions in the next two to five years.

Operational issues

Obtaining robust and comparable data on set-up and operational costs for individual infrastructures is challenging as these account for and attribute costs in different ways. Given the diversity of infrastructures, annual operational and capital costs range from £250,000 to over £4 million per infrastructure. The majority of operational costs support staff. The average UK-based infrastructure meets 69% of operational costs from public funds, 9% from the European Union (EU) and 22% from other sources (e.g. businesses or charities).

Infrastructures measure and manage their capacity in a variety of ways, for example time available on instruments, staff capacity to operate or provide access, or storage availability. For some infrastructures that operate as open access virtual resources, capacity can effectively be unlimited. The 'aimed capacity' of an infrastructure will factor-in the need for maintenance and other background processes needed to keep the resource available for users over the longer term.

We asked infrastructures about the barriers to their effective operation. The most frequently mentioned barriers were certainty of funding and a shortage of personnel and key skills (60%). These issues were often interlinked – short term funding cycles can make offering longer-term, competitive staff contracts difficult – and many made particular reference to personnel shortages in digital, data science and technical skills areas.

We are grateful to all the infrastructures which took the time to complete the questionnaires that underpin the analysis in this report. The improved understanding of the characteristics of the landscape will inform UK Research and Innovation's future infrastructure planning. We have also made additional information on UK infrastructure capability available at **www.infraportal.org.uk**

Chapter 1: Introduction

R&D has a central role to play in driving economic growth. Meeting the ambitions of the Industrial Strategy, including delivering the four Grand Challenges and the target to increase total R&D investment to 2.4% of GDP by 2027, requires investment in infrastructure as the basis of our research and innovation landscape[1]. The ability to develop new ideas and deploy them is one of the UK's greatest strengths. Today the UK is globally recognised as a leader in research and innovation, having the most productive science base in the G7 based on field-weighted citations impact and research papers produced per unit of R&D expenditure[2,3]. Every £1 spent on public R&D unlocks £1.40 of private R&D investment[4], together delivering £7 of net-economic benefit to the UK[5]. We are highly successful in translating knowledge into real-world societal, economic and international benefit – estimates suggest that more than half of the UK's future productivity growth will be driven by the application of new ideas, research and technology to create new processes, products and services[6].

These successes are in large part founded on a network of internationally competitive, high-quality and accessible research and innovation infrastructure. The UK research and innovation infrastructure landscape is diverse, from large-scale physical research facilities such as synchrotrons, research ships and scientific satellites, to networks of imaging technologies and knowledge-based resources such as scientific, cultural or artistic collections, clinical and population cohorts, archives, data and computing systems.

Access to world-leading infrastructures supports research and innovation activity at all scales, from individual investigators to large multinational collaborations. They act as a magnet to international talent and users, contribute to local and national economies and generate knowledge and capability critical to UK policy, security and well-being. Many infrastructures link to the development of key economic sectors and Sector Deals under the Industrial Strategy. Others perform vital functions for Government policy-makers including statutory functions, informing public policy, improving public services and supporting resilience and response to emergencies. Media interest in infrastructures such as the Large Hadron Collider (LHC) at CERN inspires and excites the public and the next generation[8]. Such infrastructures generate and transfer knowledge in science and technology, train highly skilled people and collaborate with industry as a consumer and a provider of technology[9]. They are a cornerstone of the knowledge economy and sit in the centre of the research, education and innovation triangle.

As set out in the Industrial Strategy Green Paper and the UK government's International Research and Innovation Strategy[10], UK Research and Innovation is undertaking a programme to understand the UK's research and innovation infrastructure capabilities to guide decision-making and support the identification of priorities to 2030. Determining the future needs first requires a solid understanding of the current infrastructure landscape. This report provides a picture of the UK's infrastructure landscape in 2018/19 using data from almost a thousand infrastructures and institutions. It builds on the Initial Analysis[7] of the UK's landscape of infrastructures published in November 2018 and captures additional work to fill gaps in the data and explore key issues in more depth.

1.1 Scope and definition of research and innovation infrastructure

The term 'research and innovation 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[11]:

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

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

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

We have also focused on infrastructure funded largely through public sector research and innovation funders. This means we have not sought to capture capability funded solely through private or charitable means. However, we recognise that partnership with the third sector and shared facilities with industry and public services such as the NHS are also vital to the UK and that many existing collaborations and partnerships already draw on this capability. Future analysis could develop this theme further.

We have considered infrastructure with a range of primary functions, structured under the broad sectors used by ESFRI to support alignment of activities.

- Biological sciences, health and food (BH&F)
- Physical sciences and engineering (PS&E)
- Social sciences, arts and humanities (SSAH)
- Energy (Energy)
- Environment (ENV)
- Computational and e-infrastructure (E-INF)

However, few infrastructures support just a single sector even when using definitions as broad as these six and we recognise that most infrastructures serve more than one.

1.2 Infrastructure diversity

Infrastructures come in many different guises. One way of thinking about them is to consider their form. Is the infrastructure composed of a specific resource – such as a collection of artefacts – or does it provide support structures to gain meaning from these resources – such as a telescope or high performance computer? The resources can be physical (e.g. electron microscope, particle accelerator) or virtual (e.g. data sets, digital images) and some infrastructures may fall into all three categories (Figure 1.1). All require specialist skills and expertise, plus operational resources, such as electricity or cooling, to function.

Infrastructures also vary by their access mechanism and structure. They may be accessed in person, used remotely, or accessed via virtual (digital) mechanisms. Some may offer multiple options. For example, a natural history collection in a museum may allow researchers to have direct access to specimens, may offer a remote access service where specimens are sent offsite to users and may provide digitised collections of the specimens online.

Figure 1.1. Types of research and innovation infrastructures.

Many infrastructures are distributed across multiple sites and may have formed from networking existing facilities or resources. These distributed infrastructures organise in different ways, e.g. using a hub and spoke model with a headquarters or coordinating hub and multiple spokes or nodes. Some global infrastructures have multiple tiers with continental and national nodes. Other distributed infrastructures have equal partnerships rather than a hierarchical model. A few infrastructures cluster with a coordinating infrastructure providing additional, organisational functions, such as the Centre for Longitudinal Studies with the National Child Development Study, 1970, Millennium and Next Steps cohort studies, all of which are infrastructures in their own right. A description of the classification we have used in this report is shown in Figure 1.2.

1.3 Scale and coverage

The Initial Analysis[7] of the UK's landscape of infrastructures provided an early snapshot of our understanding based on data provided through approximately 750 in-scope questionnaire returns. Its publication also allowed us to identify and fill gaps in our data, yielding over 100 additional questionnaire returns and improving coverage of some subsectors. Infrastructures ranged in scale from the regional to the global and from those employing a handful of staff to those employing hundreds or more.

To improve our ability to draw conclusions across these different scales, we classified all questionnaire returns according to model outlined in Figure 1.2 and Table 1.1. This report presents analyses from returns that were classified as either coordinating infrastructures, infrastructures or national nodes of international infrastructures. For the overarching chapters (Chapters 1-8) we have focused on infrastructures with national or international significance, although regional infrastructures are included in sector chapters (Chapters 9-14) to develop a deeper understanding of the infrastructure strengths in these areas.

Clusters (out of scope)
A cluster of institutions with associated infrastructures, such as a campus, science park or university consortium (e.g. the N8 group of universities).

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Institution (out of scope)
An institution whose core purpose is more than to operate a single infrastructure. Either the institution houses multiple infrastructures and/or it performs significant other functions, such as public engagement. Examples include universities and national labs.

Figure 1.2. Above and right
Description of the organisational classifications used in this programme.

Coordinating infrastructure (in scope)

An infrastructure in its own right that coordinates other infrastructures within it. An example could be the Centre for Longitudinal Studies that also hosts four distinct cohort infrastructures. It differs from an institution in that it does not perform significant other functions. Many distributed ESFRI projects are coordinating infrastructures.

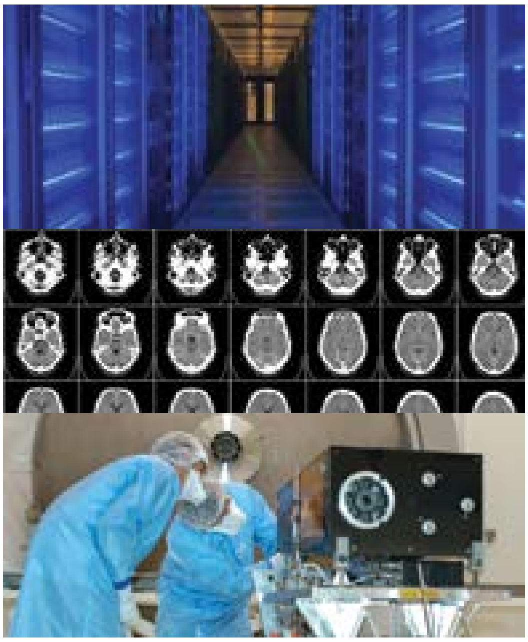
Centre for Longitudinal Studies

Infrastructure (in scope)

Facilities, resources and services that are used by research and innovation communities to conduct research and foster innovation in their fields and provide a distinct capability.

Infrastructures can be physical or virtual resources, or the facilities, instruments, tools and techniques that support them. They can be located at a single site, mobile or distributed across many places.

A single infrastructure can also be an institution, e.g. Diamond (Diamond Light Source Ltd). It would be categorised as infrastructure if it did not perform significant other functions (e.g. teaching, outreach).



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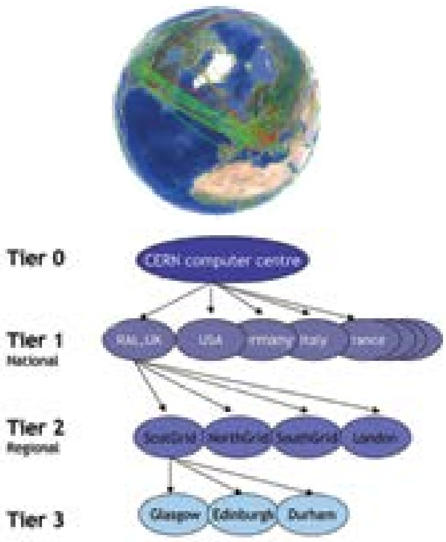
Infrastructure nodes

A component part of a distributed infrastructure is a node. Nodes may be equal in stature or operate on a tiered basis. In an international infrastructures there is typically a single headquarters and a number of national nodes in its member countries and each national node may have sub-nodes (Tier 2 or 3). National infrastructures can have a similar set-up.

(in scope) National nodes (including their regional component parts) of international infrastructures were in scope for this project, including headquarters.

(out of scope) Sub-nodes (Tier 2 or 3, regional and local nodes).



CERN Image © NASA

Table 1.1. Definition of capability scales used in this programme. Infrastructures, coordinating infrastructures and national nodes that were international or national in capability are included throughout the analyses presented. Infrastructures that are Regional in capability are included only in sector chapters (Chapters 9-14). Infrastructures that are Local in capability are out of scope for this programme.

International	Only capability of its kind in the UK. Other similar capabilities may exist in other countries or it may be one of a kind globally. Differs from a national infrastructure in that it has an international reputation, with strong international draw
National	One of only a handful of capabilities in the UK or the only one in the UK. Differs from an international capability by being more nationally focused, although it may have some international users or collaborate internationally
Regional	Infrastructure capability replicated in the UK at a regional level. It is likely to be the only one in the region, or one of a small number in the UK
Local	Infrastructure is one of several similar capabilities in a region (regions such as Wales or in the south-east of England). Out of scope for all analyses

1.4 Questionnaire methodology, limitations and potential bias

This analysis draws heavily on information gathered from self-reported questionnaires, supplemented by knowledge gleaned from interviews and workshops (see Annex B for detailed methodology). Questionnaires were designed to interact with existing and planned infrastructures at all stages of their lifecycle. In spring/summer 2018 a broad-scope initial questionnaire and optional focused second questionnaire were open for completion. A combination of methods were used to identify and target infrastructures for the questionnaires. Infrastructures identified via a desk study and consultation were invited directly. Also, an open link was advertised on the UK Research and Innovation website and disseminated through various mechanisms, including direct engagement with Higher Education Institutions (HEIs). After analysis of these initial two questionnaires a small number of key areas were identified to target in a final wave of engagement. For this final engagement both questionnaires were combined.

The questionnaire approach allowed us to gather the information to support the landscape analysis and reach a broad audience compared to alternative methods of interaction such as interviews. All questionnaires are subject to limitations and bias and it is important to understand these when reading this report (see Annex B). Given that engagement with the UK's infrastructures at this scale has never been attempted before, the data we have obtained is a healthy achievement and provides appropriate information for this report. However, no questionnaire will ever engage every infrastructure and this report, whilst broad, cannot represent the entire UK landscape. Many factors may have influenced the quality and quantity of information we were able to gather:

- Differences in the motivation and encouragement of different groups of infrastructures to engage and complete our questionnaires
- Differences in how entities interpreted the definition of an infrastructure and individual questions
- Completion rates for optional survey questions varied
- The data only represent a snapshot in time
- Validation of self-reported information is limited

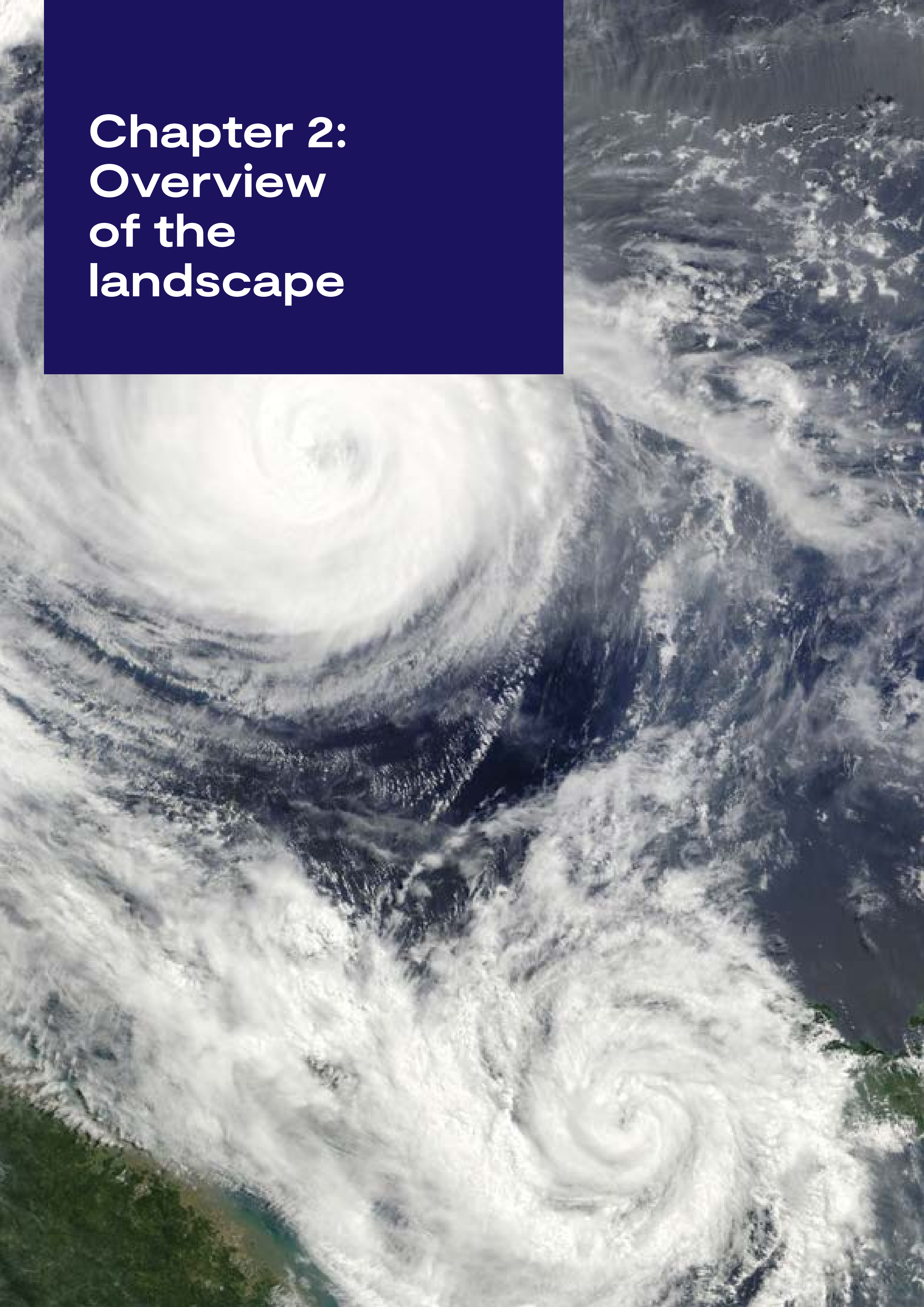
We have taken steps to minimise or mitigate the risk that variation in the quality or quantity of data would cause a bias in analysis of the landscape. In summary this has included:

- Validation of engagement coverage by cross-referencing existing catalogues (e.g. ESFRI) and other stakeholder groups
- Gap-identification and targeted approaches following spring/summer questionnaire campaigns to improve coverage
- Development and application of a categorisation model for type and scale of infrastructure (Figure 1.2, Table 1.1)
- Exclusion of questions where sample sizes were low (e.g. optional questions, small sectors) or where there were concerns over the quality of data or interpretation of the question. Not every analysis was drawn from the same sample size and no analysis has been conducted where the sample size was insufficient to draw conclusions
- Conclusions drawn only when demonstrated by a strong and clear pattern in data. No conclusions were made where differences were small or when not backed up by additional insight (e.g. consultation or interviews)

Overall, a proportionate approach has been taken with respect to drawing conclusions from questionnaire data and the analysis has been used to support other sources of understanding rather than replace them.

Further details are presented in Annex B: Methodology.

Chapter 2: Overview of the landscape



The UK has a rich and diverse landscape of research and innovation infrastructures with over 750 that report at least a regional significance. There were 945 individual responses to the questionnaires in total (excluding duplicate responses). For the purposes of further analysis, after verifying the quality and completeness of the questionnaires, the data set was restricted to those that we categorised as either:

- Infrastructures
- Coordinating infrastructures, or
- National nodes of international infrastructures

and were at least regionally or nationally/ internationally significant. Of these, 224 were regionally significant and 527 were nationally or internationally significant. These form the data sets used for subsequent quantitative analysis in this report. For Chapters 2-8 discussions are limited to the 527 infrastructures of national or international significance. The sector chapters (Chapters 9-14) draw on the broader sample of 751 infrastructures of regional significance or greater to enable a more detailed understanding of these areas.

There are a number of reasons why 194 questionnaire responses were excluded from quantitative analyses. Just over a quarter represented collections of infrastructures at a greater scale than our criteria, such as a campus or an institution, where data for functions other than infrastructures were included and inseparable. For example, a response for an entire museum may include cost and staffing data for outreach purposes and a university department may do so for teaching. Where possible these contributors were re-approached for clarification and if necessary to provide data for their infrastructures separately.

If new data were not received, appropriate insight from these questionnaires about the infrastructures themselves was included for descriptive purposes but their data do not appear in the analyses presented. Just over a third of excluded questionnaire responses were from infrastructures at a smaller scale than covered by the roadmap programme, such as those covering small pieces of equipment or a local node of a national infrastructure. The rest failed other criteria checks, such as providing access to individuals from outside the host institution, or were incomplete responses.

The reasons behind the exclusions are shown in Figure 2.1.

Infrastructures are located in all regions of the UK. The questionnaire identified a further forty-seven infrastructures located outside of the UK in at least twenty-five different countries that provided privileged UK access, e.g. through UK funding or membership partnerships. As 84% of infrastructures are housed within other institutions, primarily HEIs, the pattern of infrastructure distribution within the UK follows the general pattern of national research and innovation funding.

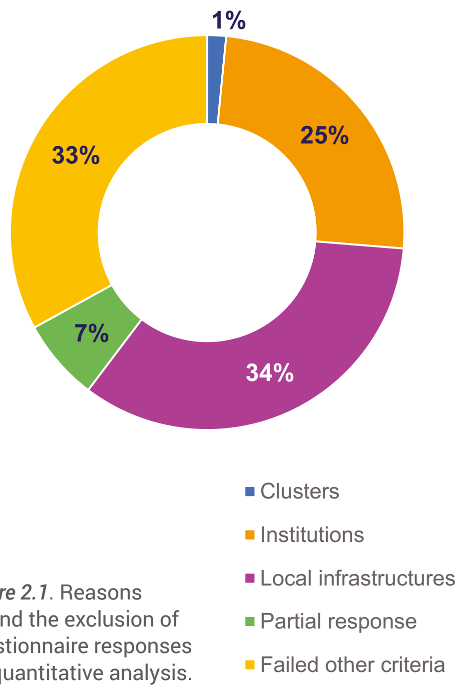


Figure 2.1. Reasons behind the exclusion of questionnaire responses for quantitative analysis.

2.1 The cross-disciplinary nature of infrastructures

Research and innovation infrastructures occur both within and across sector borders. Each sector is different both in size and in many of its characteristics. Infrastructures were asked to select the primary sector they identified with (Figure 2.2). The physical sciences and engineering and biological sciences, health and food sectors had the largest proportion of infrastructures that identified them as their primary sector (29% and 26% of the total respondents), as would be predicted by the broad coverage of these sector domains.

The smallest number of responses came from the sectors with a narrower or more defined scope, energy and computational and e-infrastructure. These two sectors had previously conducted studies to identify all of the infrastructures within them. This questionnaire reached most of these within the computational and e-infrastructure sector and over half within the energy sector.

Research and innovation is rarely contained within a single domain. Ninety-two per cent of infrastructures worked across more than one sector (mean = 3.7 sectors, median = 4 sectors, i.e. three sectors in addition to their primary domain). The number of sectors engaged with varied depending on primary sector (Figure 2.3). Infrastructures in the computational and e-infrastructure sector had the broadest reach, with 78% identifying with three or more additional sectors and 45% identifying with every sector, which reflects the pervasive role of many such e-infrastructures. The environment sector had the next broadest reach with over three quarters identifying this as their primary sector also identifying with three or more additional sectors. Fifteen per cent of infrastructures covered all six sectors.

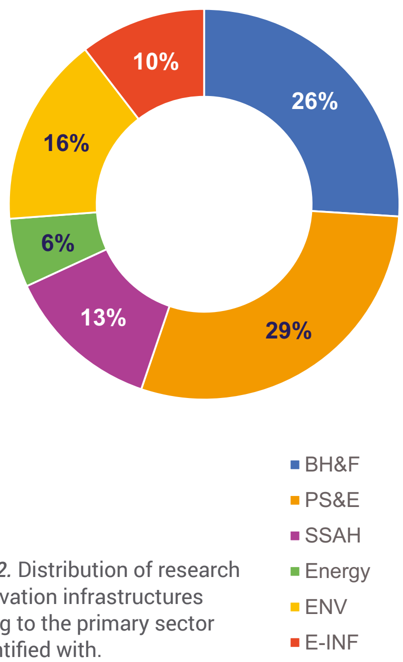


Figure 2.2. Distribution of research and innovation infrastructures according to the primary sector they identified with.

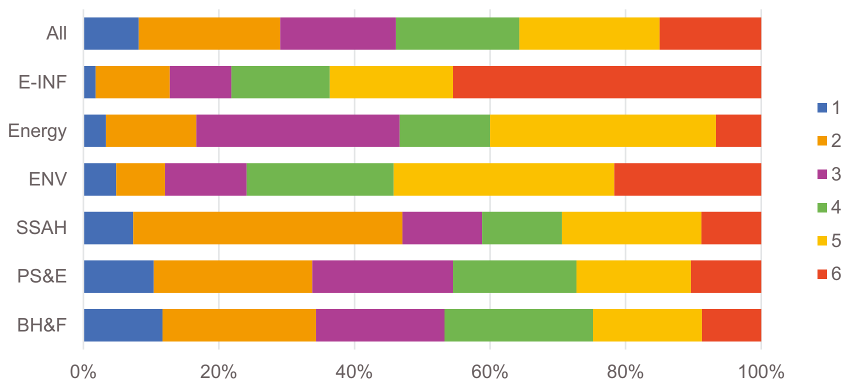


Figure 2.3. Number of sectors that infrastructures from the different sectors engaged with.

Case study: UK's national ore collection greens the search for scarce resources

The Natural History Museum's ore collection holds more than 15,000 specimens from across the globe and is one of the world's foremost mineral deposits collections. Using this reference library of the different physical and chemical properties of ores, museum scientists and curators help natural resource companies reduce the cost and ecological footprint of exploration for new metal deposits, develop more environmentally sustainable processing technologies and train geoscience students and professionals.

The museum is similarly helping optimise the recovery of e-tech metals like rare-earth elements and indium and identify new sources and extraction techniques for lithium and cobalt, increasingly used in lightweight, rechargeable batteries that power portable technologies and electric vehicles. In addition a new multidisciplinary initiative between life and Earth scientists is currently examining how the interaction between organisms and minerals in soils at contaminated sites might be harnessed to develop better strategies for the rehabilitation of former mine sites.

Natural History Museum (NHM)

The ore collection, which has been developed through museum scientists' fieldwork over the past 200 years and donations, forms part of the eighty-million-strong natural science specimens held by the museum, the national collection. It is an important resource for scientists in the UK and globally. The museum's collection includes specimens from expeditions to the Chilean Andes' Maipo valley, to shed light on the formation of copper deposits.

NHM

2.2 Large-scale, multi-sector facilities

The UK supports access to a number of large-scale facilities that are established with the intention to serve a wide multitude of sectors, both in the UK and overseas. The UK has a strong track record in establishing and operating such facilities. They often operate for many decades, take many years of planning and are technically complex necessitating delivery through national-and international-scale collaborations (Figure 2.4). They are designed to support users from across academia and business sectors with skilled technical staff working closely with visiting researchers. Cross-fertilisation of ideas is stimulated at such facilities where users bring a variety of research questions and innovation challenges. These facilities are dedicated to characterising and imaging the molecular and atomic structures of inorganic and biological materials using a range of techniques such as synchrotrons, conventional and free-electron lasers (FELs), X-rays, neutron reactors or spallation sources. They have applications in areas as diverse as clean energy and the environment, drug design, advanced engineering and electronics.

Case study:
The European Synchrotron Radiation Facility (ESRF)

ESRF

ESRF in Grenoble is the world's most intense X-ray source. Nearly 9,000 scientists from around the world visit the facility every year to conduct experiments in fields including life sciences, chemistry, material physics, cultural heritage and environmental sciences. Industrial applications include pharmaceuticals, engineering, nanotechnologies and semiconductors.

Thirty years ago the ESRF was the world's first third-generation synchrotron and since then it has contributed to over 30,000 publications and three Nobel Prizes. The facility continues to revolutionise synchrotron science with the design and construction of the Extremely Brilliant Source upgrade that will be the world's first fourth-generation synchrotron when the facility reopens to users in 2020.

The UK is a partner in many international large-scale, multi-sector facilities including the Institut Max von Laue – Paul Langevin (ILL), European Spallation Source (ESS), European X-ray Free-Electron Laser Facility (EU-XFEL) and European Synchrotron Radiation Facility (ESRF). UK-based large-scale facilities are based at the Rutherford Appleton Laboratory (RAL) on the Harwell Campus. These include the Diamond Light Source, the Central Laser Facility (CLF) and the ISIS Neutron and Muon Source. This co-location at Harwell allows cross-fertilisation of ideas that can lead to new products, services and business opportunities. These facilities support research and innovation across sectors. The connection to the wider research and innovation base are enhanced by complementary support facilities including the Research Complex at Harwell (RCaH). RCaH houses CLF lasers, imaging equipment and sample preparation suites for samples having short lifetimes or that cannot travel great distances.

The UK is involved in the development of a large-scale, multi-sector facility that is being constructed in Sweden, the European Spallation Source (ESS). Its role in its construction includes a number of 'in kind' contributions of technology developed with UK partners and industry, thereby building the UK's skills base and contributing to the UK's local economy. The technology will form part of the accelerator, the neutron-scattering systems and the target systems. ESS will be the world's most powerful neutron source and will provide new opportunities for researchers in a broad range of scientific areas including life sciences, energy, environmental technology, cultural heritage and fundamental physics and complement the capability of our national neutron facility, ISIS.

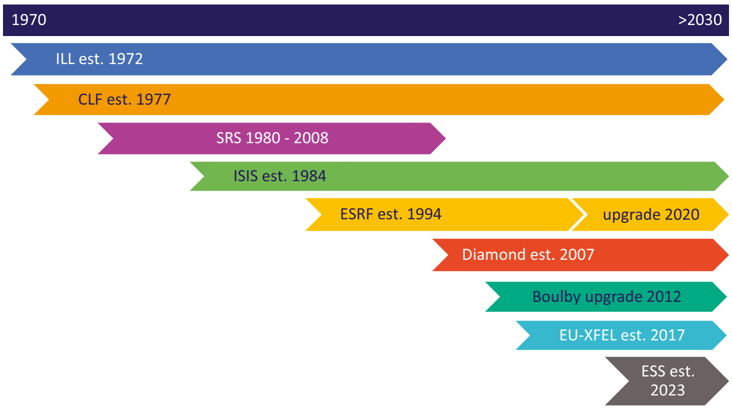
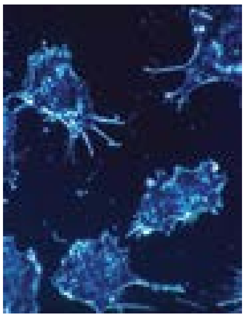


Figure 2.4. Timelines of large scale multi-sector infrastructures.

Some examples of the socio-economic outputs from large-scale multi-sector facilities:



Health services. In cancer, some receptors are 'hijacked' to drive tumour formation. In personalised cancer therapy, drugs block these rogue receptors, depriving the cancer cells of vital signalling instructions and directing them toward destruction. Targeting Slit proteins and Robo receptors has long been considered a promising therapeutic approach for types of pancreatic, skin and breast cancer. However, and almost certainly due to an insufficient structural and mechanistic understanding of Robo activation and signalling, there are currently no Robo-directed drugs. Using the ESRF it has been possible to gain information necessary to design effective drugs targeting Robo receptors. In particular, it has revealed molecular sites that, when targeted by designed drugs, will allow us to manipulate activation and inhibition in patients, providing new possibilities for cancer treatments[12].

Manufacturing pharmaceuticals. A group of human proteins known as 'G-protein coupled receptors' plays an important role in various diseases including diabetes, osteoporosis, obesity, cancer, neurodegeneration, cardiovascular disease, headaches and psychiatric disorders. This makes them excellent drug targets. However, they are not always easy to study. Scientists from clinical-stage company, Heptares Therapeutics, are using Diamond to learn more about these receptors and how we can use them to design better, more effective medicines[13].

Agriculture. The wax surface on the leaves of plants, such as barley and wheat crops, acts as a protective barrier against environmental attacks including pests and water/nutrient loss and is paramount for the wellbeing and survival of all plants. Scientists at the University of Manchester have generated a model of the wax surface of leaves similar to those of wheat and barley crops, to better understand how pesticides modify these barriers. The team conducted neutron reflectometry studies at the ILL and ISIS facilities to examine the processes of water uptake in the wax films present on the surface of plants. This is the first time anyone has used extracted waxes to recreate the wax shield that plants use for protection. As a result, the new tool enables scientists to study how pesticides enter plants by crossing the wax barrier on leaves. It is another step towards fine-tuning the chemicals used in agriculture to maximise crop yields without damaging the plants[14].

Energy. Working with the Open University, EDF Energy saved £3 billion by extending the life of nuclear power stations by five years. ISIS was used to predict the lifetime of welds and the knowledge gained enabled life extensions to fifteen nuclear reactors. Benefits included providing low-carbon energy to two million homes, £650 million a year in contracts for mostly UK-based businesses to carry out the repair work and the safeguarding of 2000 jobs in the nuclear power industry.

Transport (aeronautic). A lot of research goes into creating aircraft that deliver passengers and cargo safely and efficiently. Using Diamond, scientists from Rolls-Royce have studied the impact of a strengthening surface treatment applied to aeroplane fan blades. Exploring the microstructural impact of stress on the fan blade gives us vital information to inform future aircraft design[13].

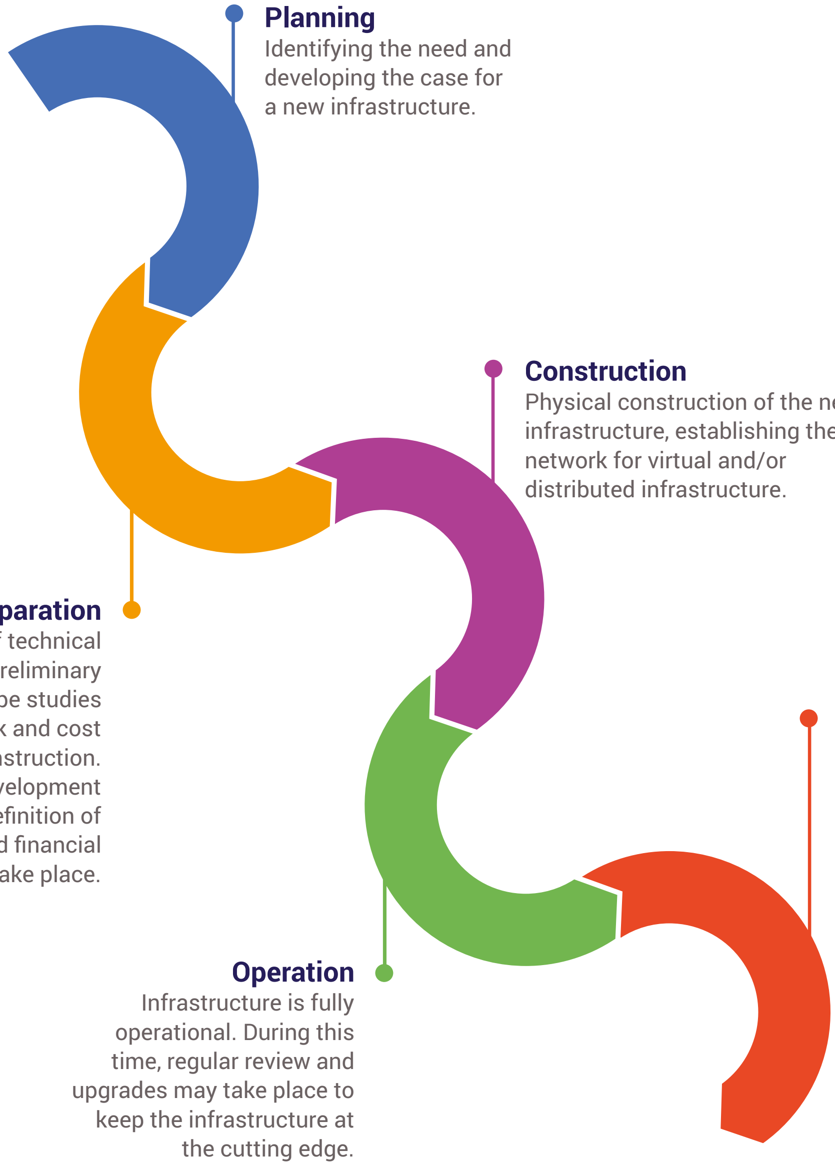
Security. Spatially offset Raman Spectroscopy, a technique developed and patented at the CLF provides a method for identifying the chemical composition underneath the surface of materials, including beneath the skin and liquids in bottles without cutting them open. The technology was commercialised through the spin out company Cobalt Light Systems, which has since been acquired by Agilent. The laser-based systems are used commercially to detect explosives in airports across the world, keeping people safer and on the move.

Chapter 3: Lifecycle

Natural History Museum

3.1 Concept

A recognised concept of the lifecycle of an infrastructure[15,16], has been adopted for the purposes of this programme. The lifecycle stages of an infrastructure follow the path of planning, preparation, construction, operation and decommissioning or repurposing (Figure 3.1). The relevance or definition of these stages can vary with the nature of the infrastructure and sector it serves. For example, for a large physical infrastructure the construction phase would encompass building and commissioning equipment. However, for a distributed infrastructure the stage might refer to the establishment of a headquarters or development of a network of distributed resources. Movement between the stages is not always clearly defined and can be a fluid process with some stages running in parallel or overlapping.



Planning
Identifying the need and developing the case for a new infrastructure.

Preparation
Refinement of technical design including preliminary scoping of prototype studies to help reduce risk and cost of financial construction. During this time, development of governance, definition of legal status and financial sustainability may take place.

Construction
Physical construction of the new infrastructure, establishing the network for virtual and/or distributed infrastructure.

Operation
Infrastructure is fully operational. During this time, regular review and upgrades may take place to keep the infrastructure at the cutting edge.

Decommissioning or repurposing
At the end of its lifecycle an infrastructure will either be shut down or may evolve to take on new functions in response to changing demand and technology.

This can be a complex process, involving careful data management, or additional funding and skills to manage any transition, environment or safety issues.

Figure 3.1. Stages of an infrastructure's lifecycle.

3.2 Current lifecycle landscape

There is a current landscape of established and operational infrastructures in the UK, with 82% reporting that they were at the operational stage. Overall, 18% of infrastructures were in early lifecycle stages (development, design or implementation). Only one infrastructure identified as being in the decommissioning/ repurposing stage and reported that the capability was being replaced by funding a fresh entity.

There has been a steady growth in the number of UK infrastructures, with more new infrastructures operating since 2010 than in any other decade (Figure 3.2). This could be driven by a number of factors. It could reflect a growth in the number of infrastructures following the injection of capital funding in the past decade in response to the increasing importance of infrastructures for solving challenges and underpinning research and innovation. There might be a higher level of responsiveness from new infrastructures that, by the very nature of obtaining funding, have recent engagement with funders. Some sectors seed a field in response to a new challenge area by funding a variety of projects in the expectation that, due to the nature of the field, only some will consolidate and be taken forward in the longer term. We will also have missed capturing those infrastructures that began and ended operations prior to this programme.

Sixty per cent of infrastructures had expected operational lifespans of over twenty-five years (Figure 3.3). There are differences between sectors. Within the computational and e-infrastructure sector where the technology used has a fast turnover rate, 42% of infrastructures have an expected operational lifespan of over twenty-five years, whereas three quarters or more of infrastructures in the social sciences, arts and humanities and environment sectors expect to operate for over twenty-five years. These include collections and data sets that increase in value over time.

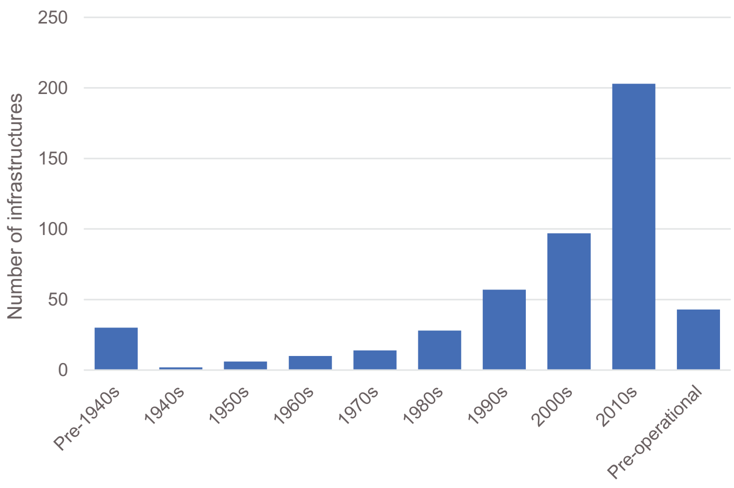


Figure 3.2. Distribution of infrastructures according to the year in which they began operations.

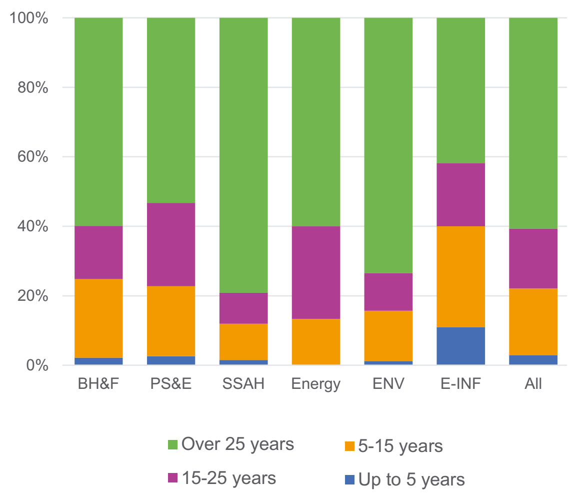


Figure 3.3. Sector differences in the expected operating lifespans of infrastructures.

Case study:
Research infrastructure for heritage science

IPERION CH established a cross-disciplinary network of over twenty partners from the UK, Europe and the USA. It connected researchers in the humanities and natural sciences and provided access to expertise, instruments, methodologies and data for advancing knowledge and innovation in the conservation and restoration of cultural heritage. The consortium brought together major centres of research in heritage science, including outstanding research institutes, as well as prestigious research laboratories and conservation centres in both museums and universities.

Networking activities promoted innovation through technology transfer and dynamic involvement of SMEs, improved access procedures by setting up a coordinated and integrated approach for harmonising and enhancing interoperability among the facilities and identified future scientific challenges, best practices and protocols for measurements and optimised the use of digital tools in heritage science. IPERION CH delivered social and cultural innovation by training a new generation of researchers and professionals, by innovation of research instruments and methods and by worldwide dissemination and communication to diverse audiences.

IPERION CH led to the establishment of a distributed European Research Infrastructure for Heritage Science (E-RIHS), which has been part of the ESFRI roadmap since 2016. The UK node of E-RIHS, UK Research Infrastructure for Heritage Science, is a distributed infrastructure on its own, with over twenty institutional partners as well as a range of research capabilities, including universities, museums, heritage organisations, digital infrastructures and laboratory facilities (such as Diamond). The mission of the international infrastructure is to stretch the boundaries and the impact of heritage science by developing the most comprehensive and advanced scientific and technological capabilities. It will enable researchers, organisations and industry to develop skills, knowledge and innovation to enable the appreciation and preservation of heritage and to drive cross-disciplinary applications of heritage science.

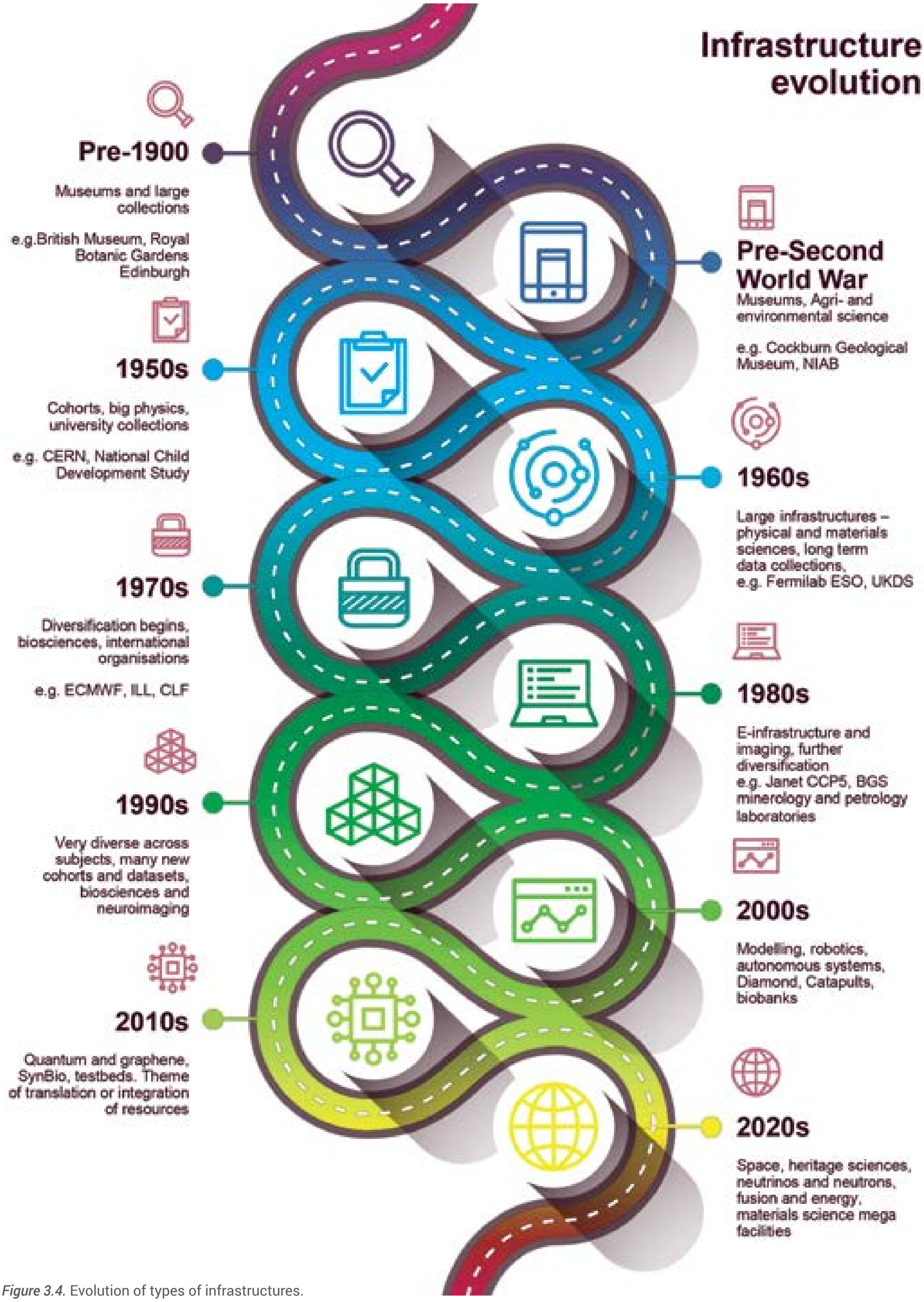


Figure 3.4. Evolution of types of infrastructures.

3.3 Evolution of the landscape

There has been a steady evolution of the types of infrastructures established (Figure 3.4). The earliest infrastructures tended to be collections housed in museums, libraries or gardens. After that infrastructures responded to the social and political drivers of the time, for example the increased need for food, with the first agricultural and environmental infrastructures appearing early in the twentieth century. The 1950s, 1960s and 1970s saw the establishment of some of the large organisational infrastructures such as at CERN, the ESO, Sanford and the British Library and also the initiation of long-term cohorts and data sets. The diversity of infrastructure discipline areas also began to grow. By the 1980s large compute and data infrastructures were established. Through the 1990s and 2000s diversity continued to explode. Infrastructures were established in topical areas of research and innovation; terms such as neuroimaging, autonomous systems and genetics were first seen, a trend that continued into the 2010s with many mentions of 'omics', quantum and e-infrastructure.

3.4 Lifecycle and planning

The expected operational lifecycle of infrastructures varies according to the organisational and legal model of the infrastructure (Figure 3.5). Infrastructures established as legal entities (national and international) have longer expected lifespans than those housed in other institutions. Infrastructures reliant on short-term funding are less likely to have an operational lifespan of over twenty-five years than infrastructures in other organisational and legal structures.

Despite their long lifespans, over three quarters of infrastructures stated that they are facing major decision points in the next five years and for 74% of these it falls within the next two years. Just under half of all infrastructures reported that they will face two of these major decisions in the next five years and for half of these both decisions are due in the next two years. Only 41% of respondents feel that they are able to plan beyond three years ahead, highlighting a mismatch between funding cycles for research and innovation infrastructure and planning requirements.

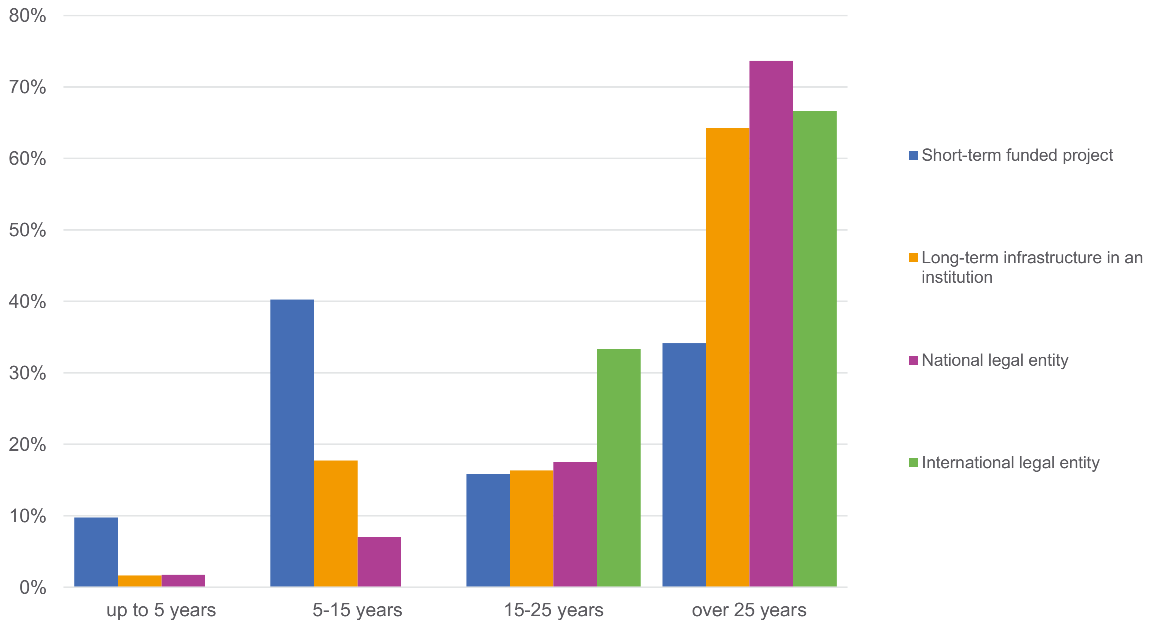


Figure 3.5. Percentage of infrastructures with expected operational lifespans from up to five years to more than twenty-five years, grouped according to their legal organisational structure.

The types of decision that infrastructures face fell into six broad categories:

1. **Financial:** a funding review or performance assessment as part of a mid-grant assessment or planned review cycle
2. **Financial:** funding has ended – usually due to the end of grant funding and the infrastructure seeking renewal to continue
3. **Financial:** significant financial changes are being considered such as a change in financial model, seeking new income sources or one-off strategic decisions that require financial support such as an upgrade or shift to operational funding post set-up
4. **Financial:** the response makes specific reference to an EU related funding decision
5. **Strategic:** a major strategic decision that will have a fundamental impact on the overall mission and purpose of the infrastructure
6. **Strategic:** a strategic choice about operations or a shift in lifecycle stage

There are overlaps between strategic choices and major financial decisions on allocations, based on the description of situations given in the responses. Just over a third were strategic in nature, related either to changes in the overall mission of the infrastructure (for example, resulting from a policy review or responding to user demand) or to the facing of major choices about their operations (often related to building location) and transition to different lifecycle stages. Two thirds of decisions were financial in nature, mostly related to the end date of existing funding and the need to apply for new funding to continue operations or the need to seek additional funding and income (e.g. for upgrades or changes in operational model such as the transition to becoming self-financing post set-up).

There is a need for continued effort in understanding the lifecycle of the UK infrastructure landscape overall and at sector level. By understanding its dynamics and evolution, its main features and challenges, the UK will be even better equipped to plan its future landscape in a way that is realistic, sustainable and agile (and therefore capable of responding to new developments) and is holistic in its approach to sustainability.

Chapter 4: International collaboration and cooperation

The Smith Review demonstrates the importance of international collaboration.Shared infrastructures are inherently collaborative and promote international cooperation, interdisciplinary research, innovation and skills training. By assembling a critical mass of people, knowledge and investment, shared infrastructures can contribute to significant regional and national economic development, attracting talent, industrial engagement and inward investment. The research and innovation infrastructure communities contribute heavily to the UK's global status in R&D.

4.1 International collaboration

Ninety-five per cent of all infrastructures collaborate in their work. Most infrastructures that collaborate do so with international partners (91%), with only 9% having national-only collaborations. When infrastructures were asked to self-identify their scope or reach, 83% of all infrastructures felt they had an international scope, which is indicative of the international nature of the research they conduct as well as of their aspirations and positioning in the global context. Almost all infrastructure (97%) in the social sciences, arts and humanities sector self-identified with having an international scope or reach.

Infrastructures are often shared and/or used by researchers and innovators from different countries, offering cost efficiencies as well as access to a broad range of facilities that otherwise would not be affordable. In some fields, infrastructures are so expensive to build and operate that their costs can be beyond the resources of a single country. Another driver for collaboration comes from the challenges and threats facing society today, which often do not recognise national boundaries and require a collaborative approach to tackle.

From the 527 questionnaire responses, 204 were classified as international. They were distributed across the six sectors in a similar pattern to the overall numbers of infrastructures, with proportionally slightly more in the environment and PS&E sectors (Figure 4.1). Physical sciences and engineering international infrastructures are characterised by having more of the very large, expensive physical infrastructures that are beyond of the scope of a single country to deliver, e.g. particle accelerators and telescopes.

4.2. Staffing

Research and innovation infrastructures are key players helping mobilise talent across the world, enriching the pool of technical skills, training the next generation of researchers and stimulating the mobility of leaders and in doing this they contribute to accelerate advances in research and technology. Infrastructures based in the UK attract significant talent from around the world, where 27% of staff come from outside the UK, more than the HEI sector as a whole (20%) (Figure 4.2). Infrastructures in the computational and e-infrastructure sector are most reliant on non-UK staff (39%).

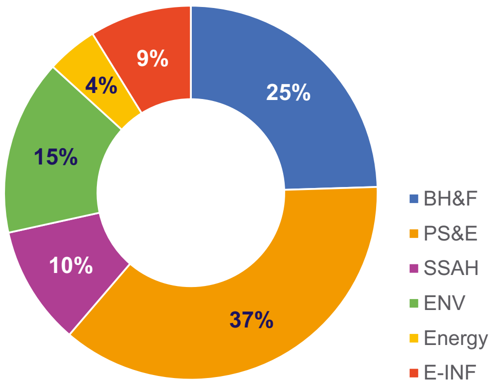


Figure 4.1. Distribution of international infrastructures across the six sectors.

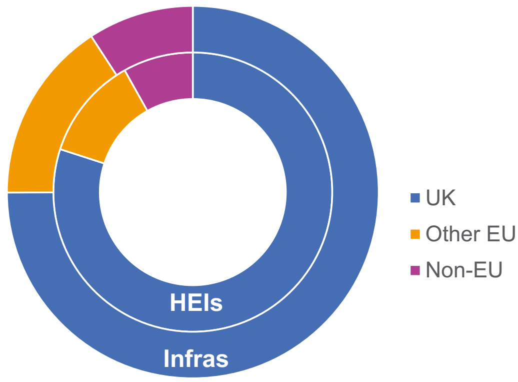


Figure 4.2. Nationality of staff employed at UK infrastructures (outer circle) and HEIs (inner circle); source Higher Education Statistical Agency (HESA) staff data 2017[17] (academic and non-academic).

4.3 International user base

In the infrastructure landscape there is a constant flow of users seeking access to the best facilities, wherever they are. In the UK 39% of individual users of infrastructures come from outside the UK and 91% of infrastructures have an international user base (Figure 4.3). Almost all infrastructures (95%) consider that there will be a change in demand by the user-base in the near future. Forty-six per cent of them think the balance will remain similar to today, 40% think it will be increasingly internationally biased and only 14% think there will be a greater national focus.

The reasons why UK-based infrastructures attract users from overseas are varied (Figure 4.4). Often it was reported to be because no similar capability exists elsewhere, it being an integral part of an international collaboration, or because it offered an overall 'package' (e.g. a support package or access to complementary facilities) significantly better than that offered by others.

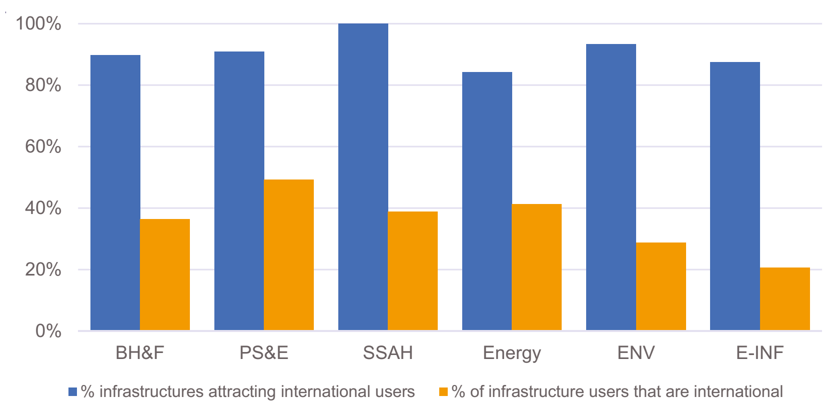


Figure 4.3. Attraction of UK-based infrastructures to international users based on their primary sector.

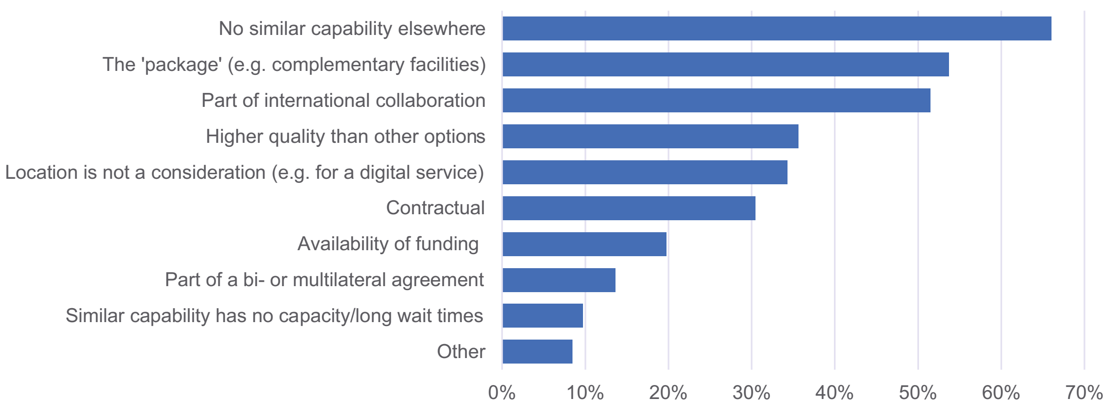


Figure 4.4. Reasons cited by infrastructures for attracting international users. Note that options were not mutually exclusive and participants could select all that were relevant.

SKA Organisation

Infrastructures are inherently international. We collaborate because many of the research and innovation challenges that infrastructures are helping to solve are global in their nature, such as changing ocean temperatures or moving vast quantities of data around the planet. Some infrastructures can only be sited in certain locations outside of the UK, such as the remote, radio-quiet regions or cloud-free skies required for astronomy facilities. Infrastructures can also be very costly, beyond the budgets of a single nation.

The SKA will be the world's largest and most sensitive radio telescope array. Whilst the ten member countries, including the UK, are the cornerstone of the project, there are around 100 organisations from around 20 countries participating in the overall design and development.

Chapter 5: Skills and Staffing

Research and innovation infrastructures of all sizes require staff with highly specialised skills to maximise the potential utility of the infrastructure, from the managers of these infrastructures to the technicians that operate them daily. Having these skills in place not only realises the day to day function of an infrastructure but also contributes to the innovation of new technologies and techniques and dissemination of good practices. To capture a snapshot of skills and staff in the current infrastructure landscape, respondents were asked to answer questions on staff numbers, sex, ethnicity black, Asian and minority ethnic backgrounds (BAME) and staff roles. Where appropriate the staffing of infrastructures has been compared to staffing across UK HEIs according to HESA 2017 data[17] combined for academic and non-academic staff.

5.1 Numbers

Staff numbers were measured as the number of FTEs to control for variation in working patterns. The 480 national and international infrastructures located within the UK employ just under 25,000 FTEs. The number of FTEs employed by each sector in the UK follows a similar pattern as the number of infrastructures in each sector but with SSAH and BH&F employing the most staff and PS&E having fewer than their share would predict (Figure 5.1). However, many large PS&E infrastructures are international facilities outside of the UK and thus excluded from this finding. The median number of staff working at each UK-based infrastructure is ten FTEs, ranging from three FTEs in the environment sector to twelve FTEs in BH&F.

Across all infrastructures regardless of location, infrastructures that are set up as their own legal entity tended to employ significantly higher numbers of staff than infrastructures that were housed in other legal entities (Figure 5.2). This pattern is partly driven by a relatively small number of very large and often international infrastructures typical of this field, such as the LHC at CERN, ESO and the High Value Manufacturing Catapult. It is also likely that internationally-hosted infrastructures may have underestimated staff numbers due to the difficulty of attributing staff working across infrastructures and other activities.

Infrastructures that were the national node of an international infrastructure had a lower headcount than those categorised as an entire infrastructure (Figure 5.3). This relates to a national node being a subset of the infrastructure's capability. Coordinating infrastructures, those that were considered an infrastructure in their own right but included other infrastructures (such as some ESFRIs), had the greatest number of staff. Similarly, staff numbers increased from those infrastructures providing a regional capability, to a national capability, to an international capability when considering the full data set of 751 infrastructures (Figure 5.4).

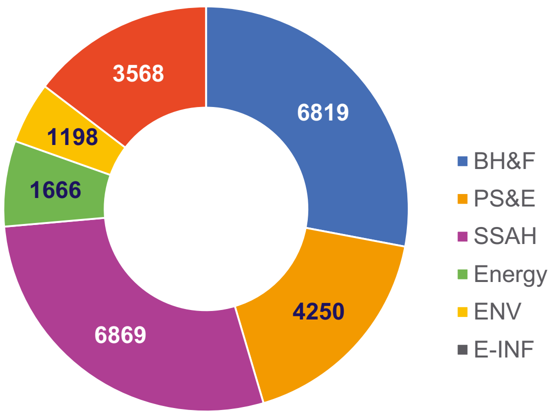


Figure 5.1. Staff numbers (FTEs) employed at infrastructures in each of the six sectors (restricted to infrastructures located in the UK).

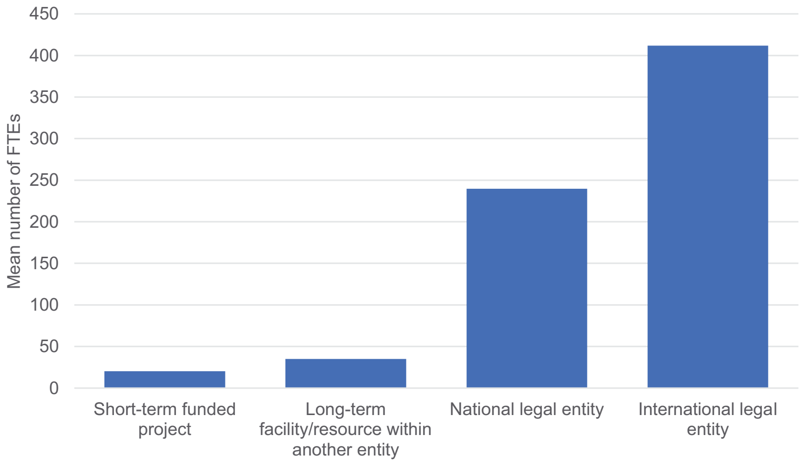


Figure 5.2. Mean staff numbers (FTEs) at infrastructures set up under different legal models. Those set up as national or international legal entities have significantly more staff than infrastructures hosted within other institutions.

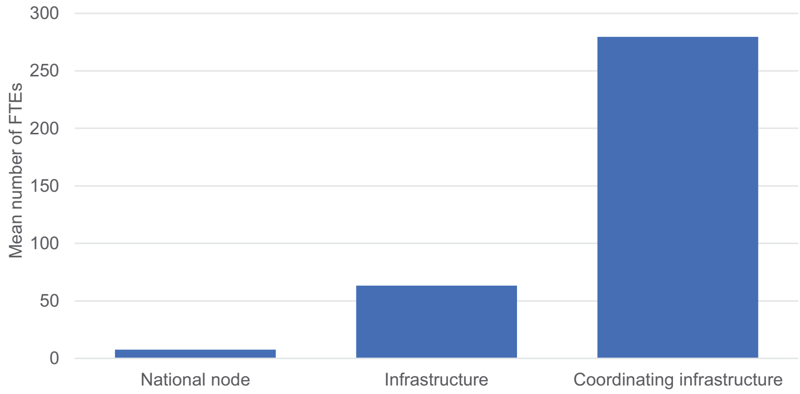


Figure 5.3. Mean staff numbers (FTEs) at national nodes of international infrastructures, infrastructures and coordinating infrastructures.

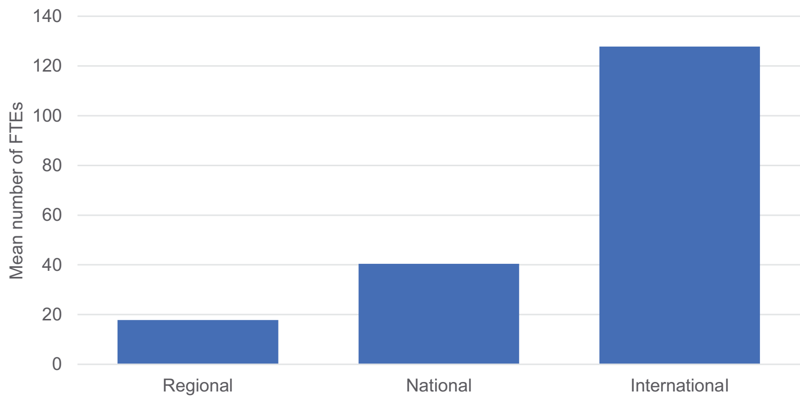


Figure 5.4. Mean staff numbers (FTEs) at infrastructures categorised as providing a regional, national or international capability. This result used the dataset of 751 questionnaire responses to include those of regional capability.

Infrastructures need a range of skills to operate. On average, 38% of staff are employed in technical roles, 33% are in research roles and 29% perform other functions such as management, administration and outreach.

5.2 Roles

Infrastructures depend on the functioning of a range of different roles that can be broadly categorised as research, technical or other (e.g. management, administration). Five of the six sectors had more than three-quarters of their staff performing research and technical roles (Figure 5.5). The social sciences, arts and humanities sector has 69% of staff listed as being in 'other roles', which includes large ESFRI infrastructures as well as museums, archives and collections. Technical roles are especially prevalent in the environment and PS&E sectors, making up around half of all roles.

5.3 Staff diversity

Infrastructures employ proportionally fewer females and a similar proportion of staff with BAME ethnicity compared to HEIs in the UK (Figure 5.6).

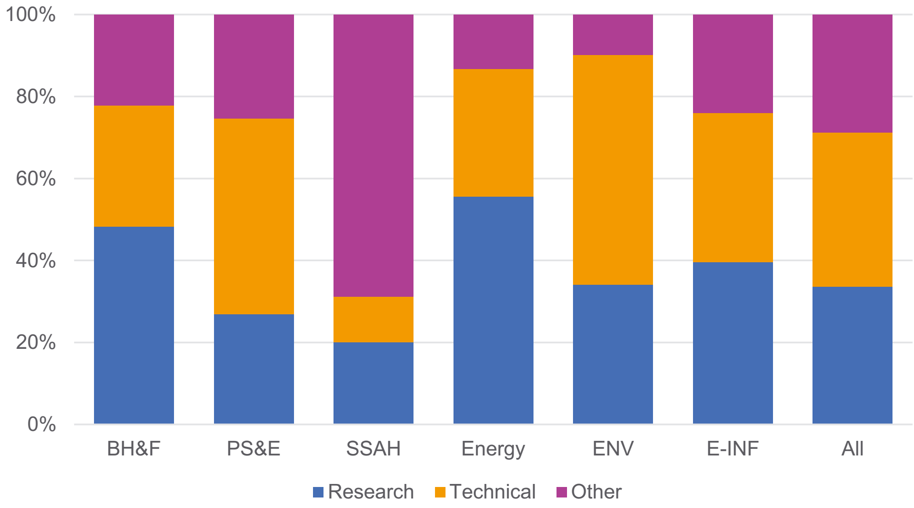


Figure 5.5. Staff roles in infrastructures. On average, 33% of staff employed by infrastructures fill research roles, 38% technical roles and 29% other roles.

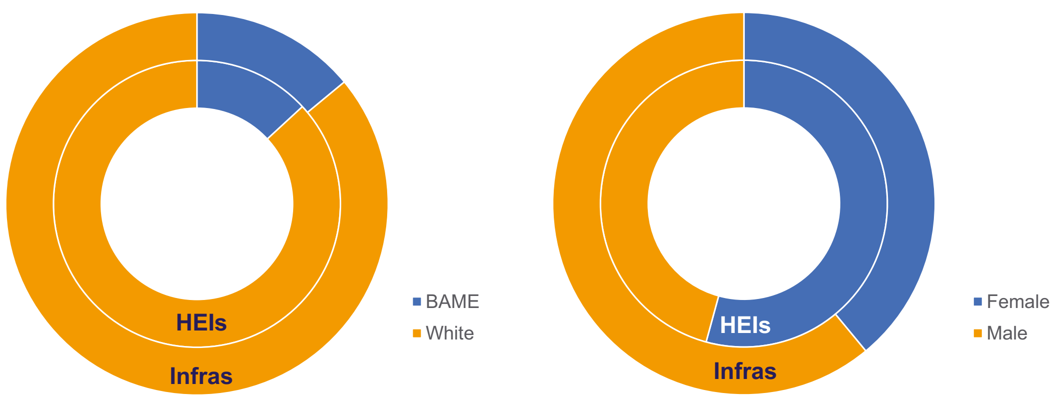


Figure 5.6. Proportion of staff employed at UK infrastructures (outer circle) and HEIs (inner circle) according to (a) ethnicity and (b) sex. Proportionally more staff employed at infrastructures are male compared to staff at HEIs (61% versus 46%). The percentages of staff of BAME ethnicity are similar for infrastructures and HEIs (14% versus 13%) (HESA staff data 2017[17]).

Case study:
The role of infrastructures in the provision of skills and training

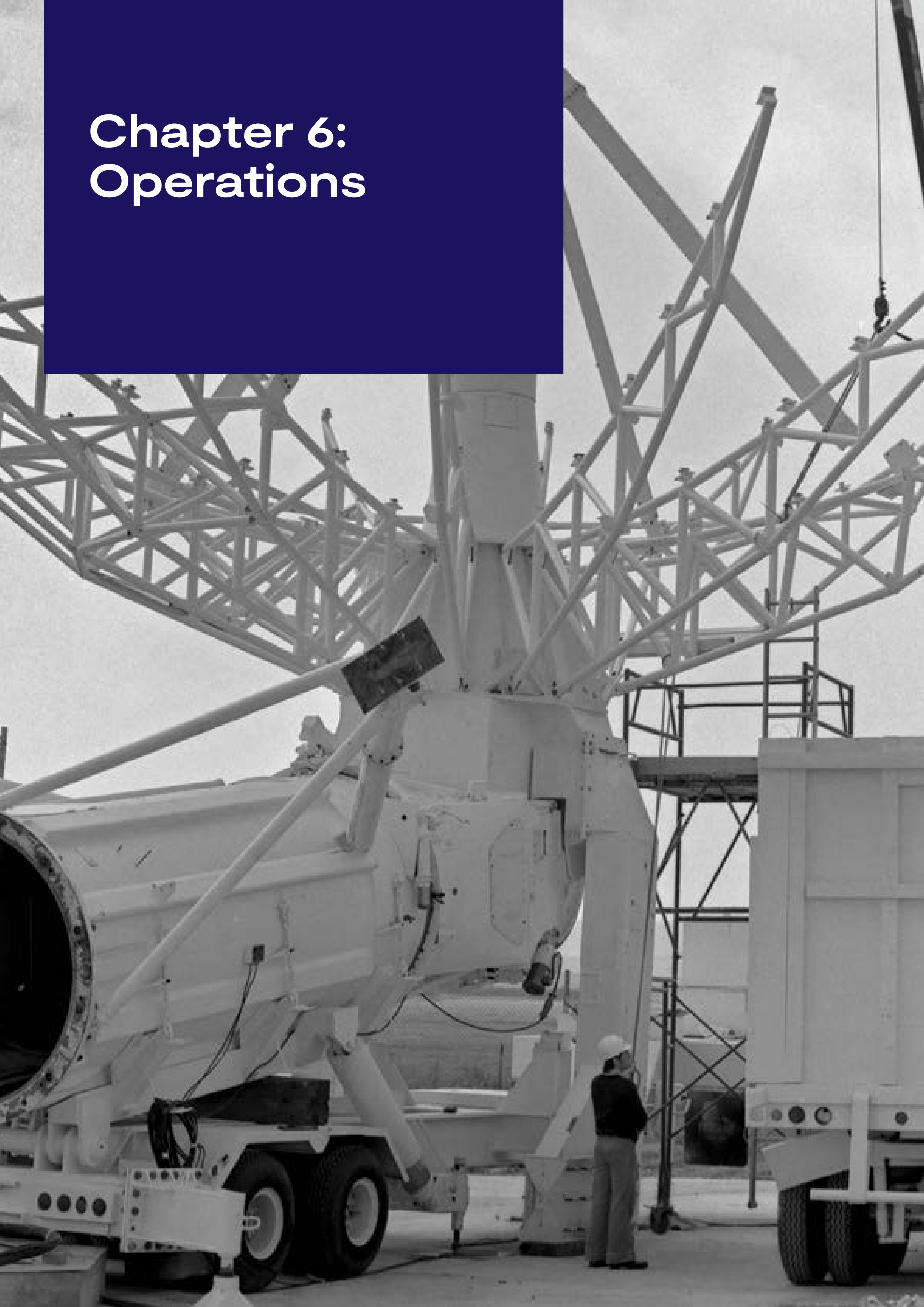
The University of Sheffield Advanced Manufacturing Research Centre (AMRC) is a network of world-leading research and innovation centres working with advanced manufacturing companies around the globe, specialising in carrying out research into advanced machining, manufacturing and materials, which is of practical use to industry.

It employs over 500 highly qualified research and technical professionals from around the globe. The research infrastructure also offers roles in management and administration. The AMRC Training Centre operates an Apprentice Training Programme that has 250-300 positions per year. The programme structure includes a two-year basic apprenticeship, a two-year higher apprenticeship and a foundation degree. As part of the University of Sheffield the apprentices can then progress to Honours, Masters, EngD and PhD levels. For the young people in the Sheffield City Region, it provides the foundation for a rewarding career in some of the world's most innovative industries.

The AMRC also offers graduate and MSc programmes for engineers. As part of the programme graduates study for a postgraduate diploma in engineering management, which is aimed at engineers who want to move into management while maintaining their competencies in technical subjects. Further to this, the Industrial Doctorate Centre (IDC) offers graduates the opportunity to learn and earn in four-year engineering doctorate programmes, which combine taught modules with original research for world-leading engineering companies. Recent engineering doctorate programmes include advanced projects for Rolls-Royce and Technicut.


AMRC

Chapter 6: Operations



Obtaining robust and comparable data on the set-up and ongoing costs for infrastructures is challenging given the diversity of activity and business models within the UK landscape. The infrastructure questionnaires asked respondents to provide the approximate costs of establishing their infrastructure and the costs of running it every year, though response rates were only 33%-48% across these questions.

As well as varying by subject area and type of research, costs depend on a range of operational and financial management issues. These include:

- The approach to calculating and accounting for overheads when an infrastructure is part of a larger organisation
- How common costs are shared between infrastructures or nodes of a distributed infrastructure
- How costs are shared between co-funders (including international partners)
- The treatment of depreciation of capital equipment
- The legal status of an infrastructure and approach to managing fluctuation in spend over time

Respondents also varied in their approach to accounting for staff costs, usually reflecting their funding model. For example, the cost of the operational staff required to run an infrastructure was usually included but the research staff may not have been if a separate funder supports projects using that infrastructure. Infrastructure managers themselves may also not be fully aware of how their host organisation attributes and manages overhead costs and this will likely vary from organisation to organisation. In general this means the figures presented here are likely to be an underestimate of the full operational expenditure associated with individual infrastructures.

Despite these challenges some broad observations can be made based on the data available. Figure 6.1 shows the diversity in annual operating and capital costs across the questionnaire responses. For about one in five infrastructures the annual cost of operations (excluding capital equipment) is less than £250,000, whilst a similar proportion (18%) have an annual operational cost of £4 million or more. The annual cost of capital, including provision, maintenance, replacement or upgrades, also varies significantly across infrastructures. The spike of 49% of infrastructures having capital costs below £250,000 is reflective of non-capital-intensive infrastructures, e.g. some infrastructures in the SSAH sector.

Given that the bulk of operational cost is often for staff salaries, there is a strong correlation between operational costs and full-time equivalent staff numbers (correlation coefficient = 0.81). Figure 6.2 shows the scatter plot for those infrastructures with less than 100 staff and with annual operational costs of £4.5 million or less. The line of best fit displays the positive association between the two variables.

Infrastructures that are short-term funded projects (e.g. the UK Multiple Sclerosis Register, a large cohort study) typically have lower annual costs than infrastructures that are either national or international legal entities (e.g. the National Composites Centre). Some short-term funded projects are long-term activities surviving between sustainable funding options. Those housed in other entities may have their costs under-reported because of overhead sharing or attribution. Long-term infrastructures located in institutions have a fairly uniform spread across the cost categories, whereas those operating as a legal entity were more likely to have costs in the higher categories (Figure 6.3).

6.1 Set-up capital costs

Many infrastructures require a significant up-front investment in capital equipment. Of those infrastructures established since 2010 that provided data on the capital cost associated with setting up, about half had a capital cost requirement of £6 million or more (Figure 6.4). Almost one in ten required £62 million or more, with international infrastructures such as the ESS requiring more than £1 billion.

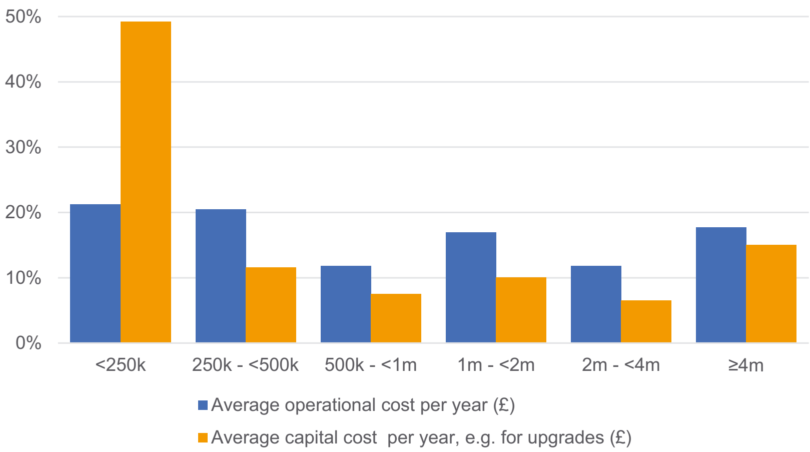


Figure 6.1. Distribution of average, annual operational and capital cost estimates for infrastructures (k = thousand, m = million).

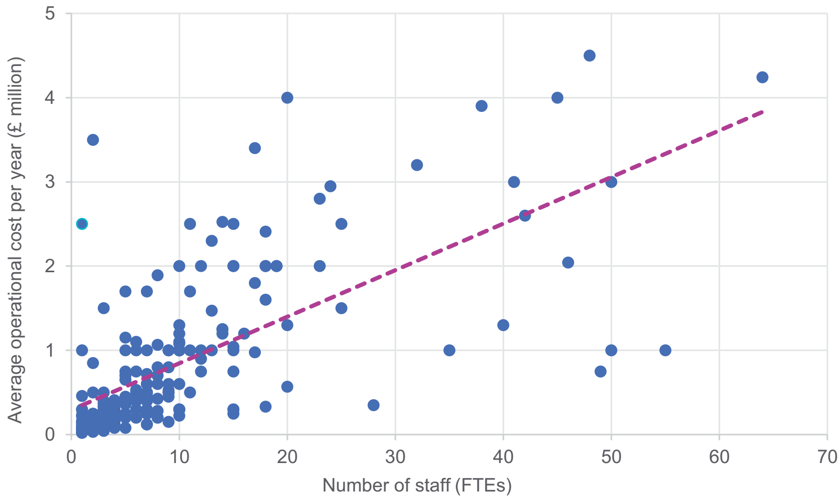


Figure 6.2. Scatter plot of infrastructures showing staff numbers plotted against average, annual operational costs (only infrastructures with fewer than 100 staff and annual operational costs of £4.5 million or less shown, though the positive association remains true for all infrastructures).

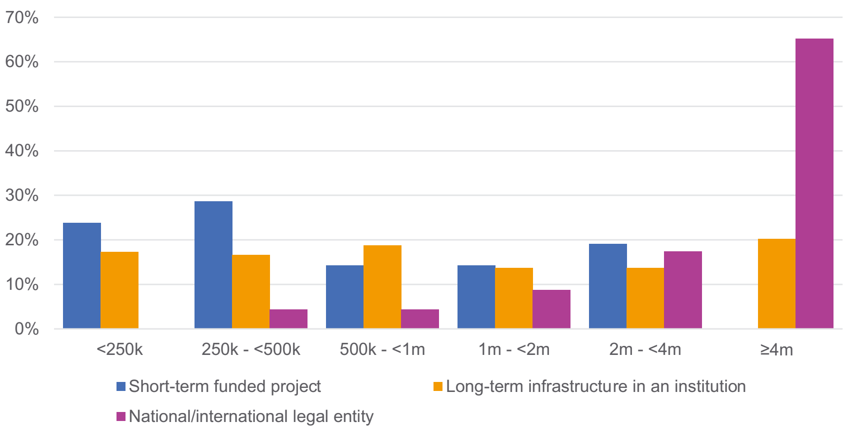


Figure 6.3. Distribution of infrastructures' total annual costs based on their legal model (k = £ thousand, m = £ million).

6.2 Sources of funding

This programme focuses on research and innovation infrastructures with a reliance on public sources of funding for establishment and/or operations. This means we have excluded from our analysis any infrastructures that stated they did not rely on public funds, although we recognise that there are important components of the UK's overall capability that are funded through charitable and private means.

The final data set confirms the patterns described in the Initial Analysis[7]. There is a great reliance on public funding to set up an infrastructure, which continues for operational costs with roughly half of respondents reliant on public funding to cover more than 70% of the cost of their operations (Figure 6.5). This is likely to be an underestimation because three quarters of respondents are based in institutions such as HEIs or PSREs and are reliant on their host organisation for a proportion of their costs (see above). This makes attribution of funding source more challenging to quantify precisely.

Operating costs are funded mostly through UK sources of public funding – the average national infrastructure covers 73% of its operating costs with UK public funds (Figure 6.6). EU funding meets 7% of the operating costs of national infrastructures and 15% of international infrastructures. It is targeted toward the early stages of infrastructures' lifecycles – bringing networks together, planning and preparation. The EU does not fund significant operational costs but it does fund access and opening

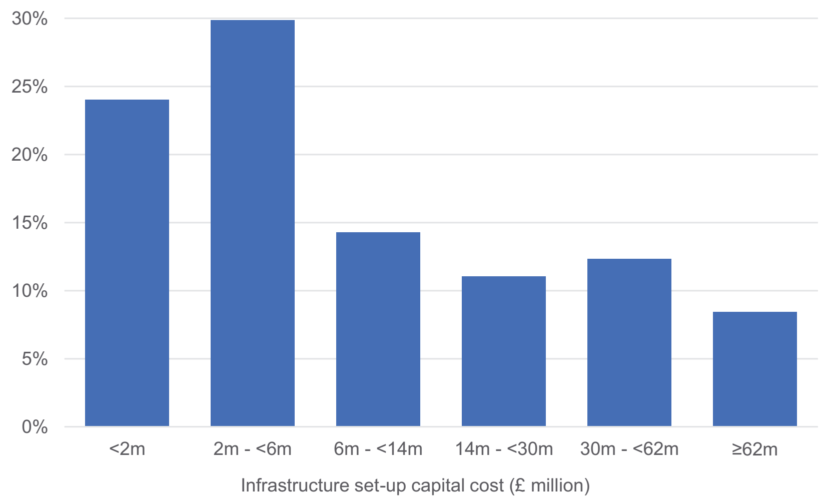


Figure 6.4. Distribution of infrastructure set-up capital cost (infrastructures established since 2010).

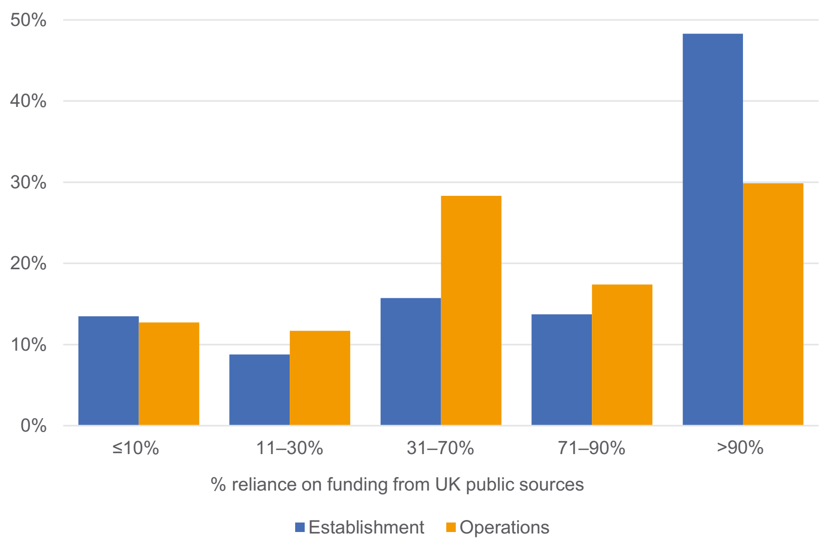


Figure 6.5. Degree of reliance on public funding for the establishment and operations of infrastructures.

up infrastructures to international users and releasing the innovation potential of operating infrastructures. Where further information was given about the 'other' sources of operational funding, this was split between commercial activity to generate income, industry and charitable funding for projects, donations and philanthropic sources, international research organisation funding (often via users from those countries travelling to access UK infrastructures) and some local authority funding. Industry funding was the most prevalent accounting for 47% of the 'other' sources.

6.3 Primary funding source

The primary public funding source was overwhelmingly the Research Councils (Figure 6.7), covering 56% of infrastructures. The reliance on the Research Councils increased to 62% when considering only those infrastructures most dependent on public funding for their overall costs (i.e. reliant for >70% of establishment costs). This reflects the Research Councils' role in supporting the types of underpinning infrastructure considered in this report and the ease of attribution of funding through grants awarded directly to an infrastructure. The remaining 44% record their primary public funder as either Innovate UK, a government department, an arms-length public body or Devolved Administration funder. The government sources most frequently mentioned as either a primary funder or a contributor were the Department for Business, Energy and Industrial Strategy (BEIS), the Department for Digital, Culture, Media and Sport (DCMS), the Department of Health & Social Care (DHSC), the Department for Environment, Food and Rural Affairs (Defra) and local sources (a local enterprise partnership or a local authority). Within the 'other' category many receive funding from multiple sources, including EU funding streams and charitable sources alongside funding from Research Councils or a university.

The role of research capital funding provided directly to universities through devolved funders (the Scottish Funding Council, Higher Education Funding Council for Wales, Department for Employment and Learning Northern Ireland and Higher Education Funding Council for England, now Research England) is complex[18,19], and likely to be under-reported. Some respondents reported or acknowledged this funding stream. However, others that were hosted within universities did not include research capital funding in their funding sources. It is likely that many of these do benefit from this devolved funding, although the precise level of support will be subject to how funds are managed within individual universities. Universities receive income from multiple sources and it was not possible to explore the precise allocation of such funds through this questionnaire.

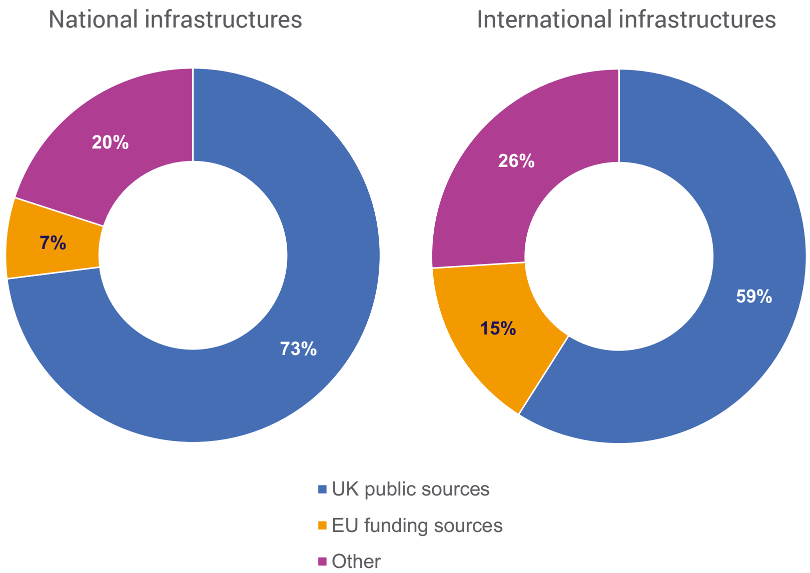


Figure 6.6. Sources of funding for the operational costs of infrastructures.

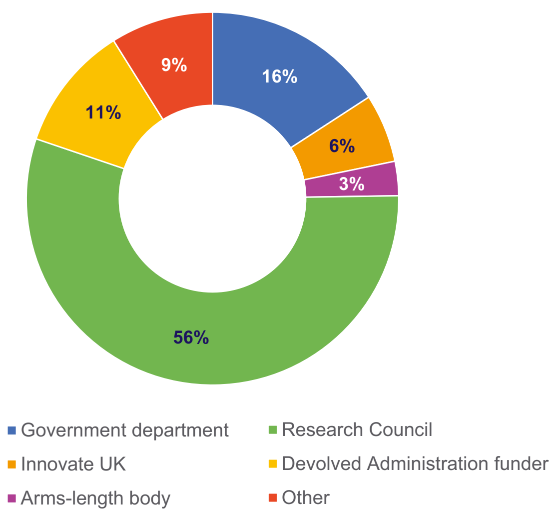
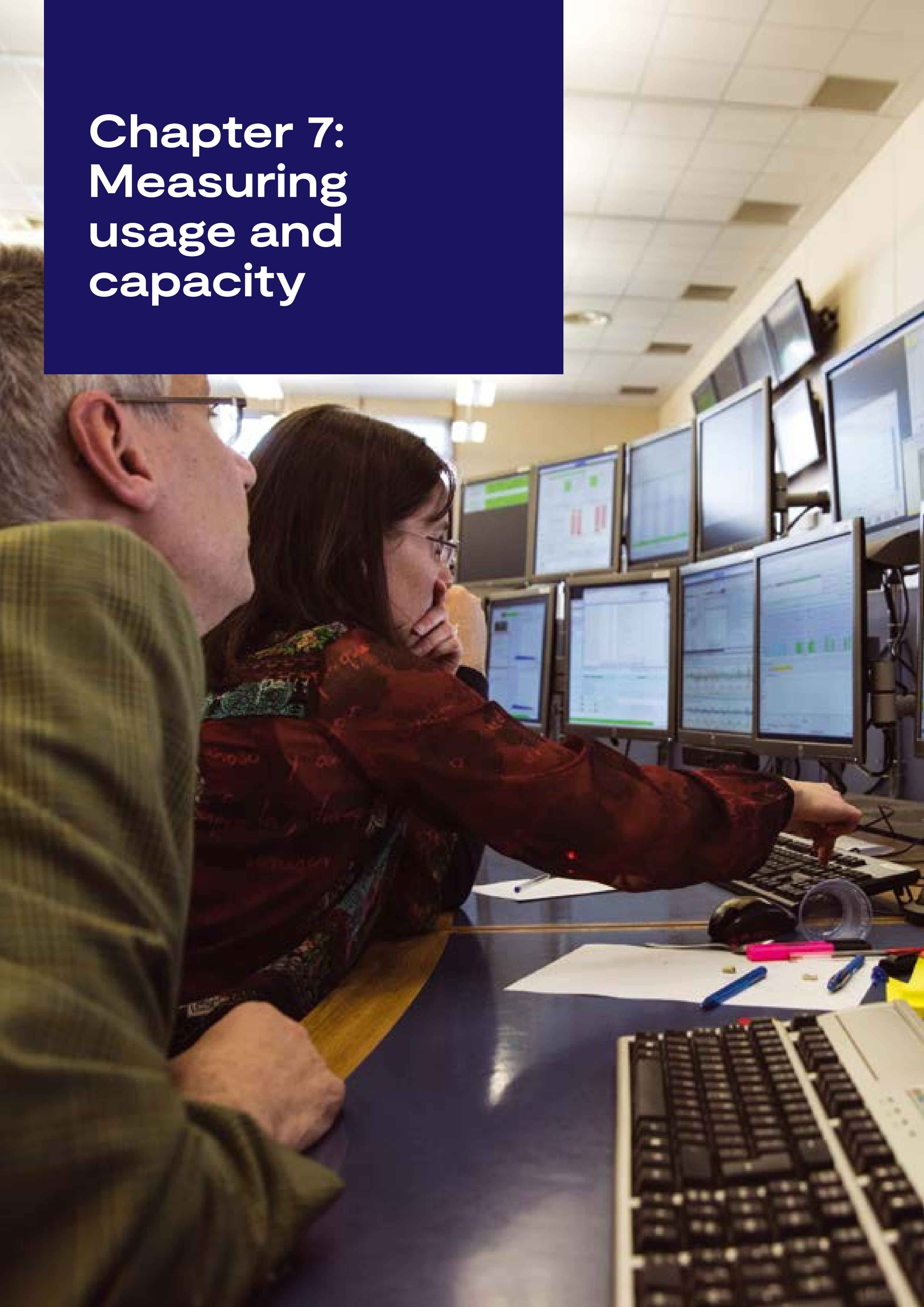


Figure 6.7. Primary source of public funding for infrastructures.

Chapter 7: Measuring usage and capacity



7.1 Usage

Measuring usage and capacity is complex given the diversity of infrastructures and range of access models. Infrastructures that have physical resources or provide facilities and equipment often record the access of individuals or groups, or may count the number of experiments performed. There are usually upper limits on the number of users that they can support, e.g. time limited equipment usage, or access to a collection limited by the availability of an expert able to interpret that collection. Such infrastructures can be thought of as having their capacity capped in some way. On the other hand, some virtual infrastructures can operate open access models and may only be limited by the bandwidth of their network or computer architectures. Rather than count individuals, groups or experiments, these infrastructures may report usage by the number of downloads performed and may have millions of 'users'. These infrastructures can be thought of as having an uncapped capacity. Nearly three quarters of infrastructures have their capacity capped in some way and 12% are uncapped (Figure 7.1).

The approach to measuring usage varies widely by sector. Infrastructures in the environment, computational and e-infrastructure and BH&F sectors reported that they made greater use of virtual access mechanisms. These areas often develop or provide access to large data sets. The average number of downloads per year within the SSAH and BH&F sectors was in the 85,000 to 110,000 range, but for the environment and computational and e-infrastructure sectors it was around 200,000,000 downloads per annum and represented over 99% of 'users'. The PS&E and energy sectors conversely did not have infrastructures where users were measured by downloads or other virtual means.

All sectors had infrastructures providing physical access to users recorded as either individual researchers, research groups or numbers of experiments (Figure 7.2). Infrastructures averaged 200-5400 individual users per infrastructure per annum in all sectors except for SSAH, which recorded significantly greater numbers. This is driven by footfall and digital access to archives, museums, libraries and other collections.

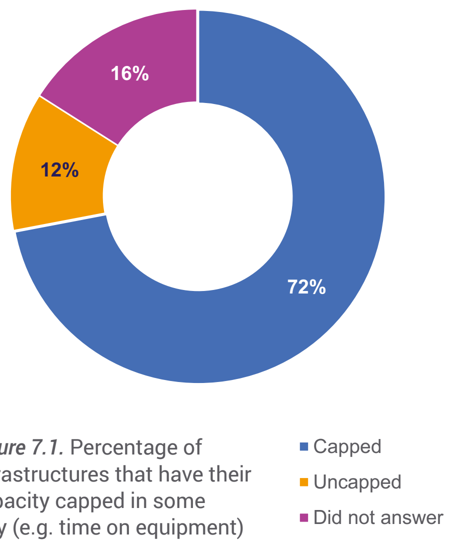


Figure 7.1. Percentage of infrastructures that have their capacity capped in some way (e.g. time on equipment) compared to those that have uncapped capacity (e.g. open access data downloads).

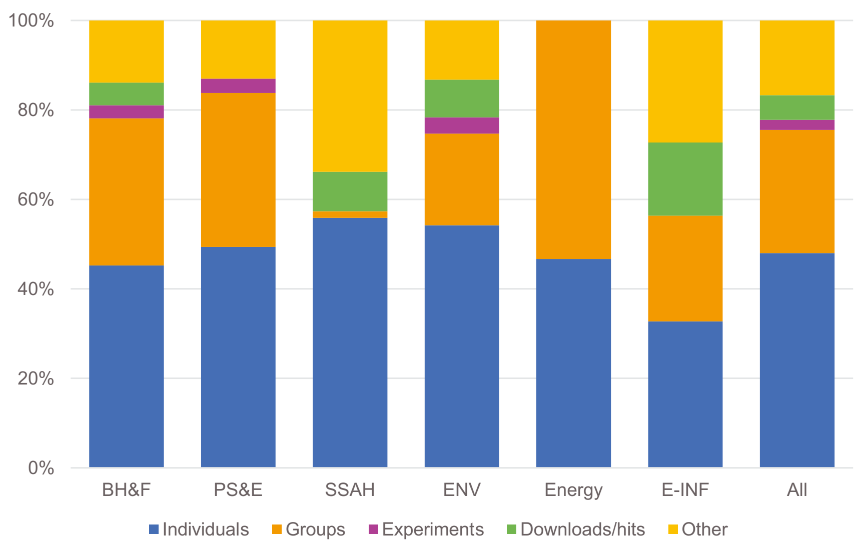


Figure 7.2. Percentage of infrastructures in each sector that measure usage according to either individuals/groups, experiments performed, downloads/hit or another measure.

7.2 Measuring capacity

An infrastructure's approach to capacity measurement is dependent on what they are set up to do. It can be focused on measures of output or, in cases where this is difficult, the ability to deliver products or services. Unlimited usage can often be made of virtual resources, such as data sets.

The varying approaches to capacity measurement described in responses to our questionnaires have been grouped into seven broad categories:

- **Output capacity:** how much the infrastructure produces, e.g. samples processed, surveys conducted, data produced
- **Operating/instrument/experiment time (hours, days, weeks):** the 'up-time' of the infrastructure
- **Number of users/experiments:** the number of users/experiments that can be served or facilitated
- **Space/equipment/resource availability:** the amount of the capabilities needed by researchers/innovators that the infrastructure can provide
- **Staff availability**: the number of staff, or staff time
- **Computing power:** specific for e-infrastructure
- **Online resources/collections/data:** capacity cannot be measured and near unlimited use can be made of the infrastructure

These categories are not mutually exclusive and many infrastructures talked about their capacity in multiple ways; for example, operating time and staff availability could be paired due to machines being unusable without key staff. Figure 7.3 shows the percentage of infrastructures in each sector that described their capacity according to the above categories. The percentage of infrastructures that did not answer the question is also shown. Whilst the question was optional and some non-response was expected, non-response was also driven by capacity measurement being less meaningful for certain infrastructures, including those with no constraints on use (e.g. some open access online resources).

Differences in sector responses about measures of capacity are indicative of the types of infrastructure in each sector. Infrastructures in the energy, PS&E or environment sectors commonly spoke about capacity in terms of operating/instrument/experiment time. About 30% of BH&F infrastructures mentioned staff availability when describing capacity. A relatively high percentage of computational and e-infrastructures mentioned space/equipment/resource availability, which is partially related to virtual storage space, alongside measures of computing power. About 30% of operational SSAH infrastructures did not answer the question around capacity measurement, which could reflect the challenge of separating visitor numbers for engagement purposes with those for research purposes (e.g. in a museum or library), or that footfall is not measured.

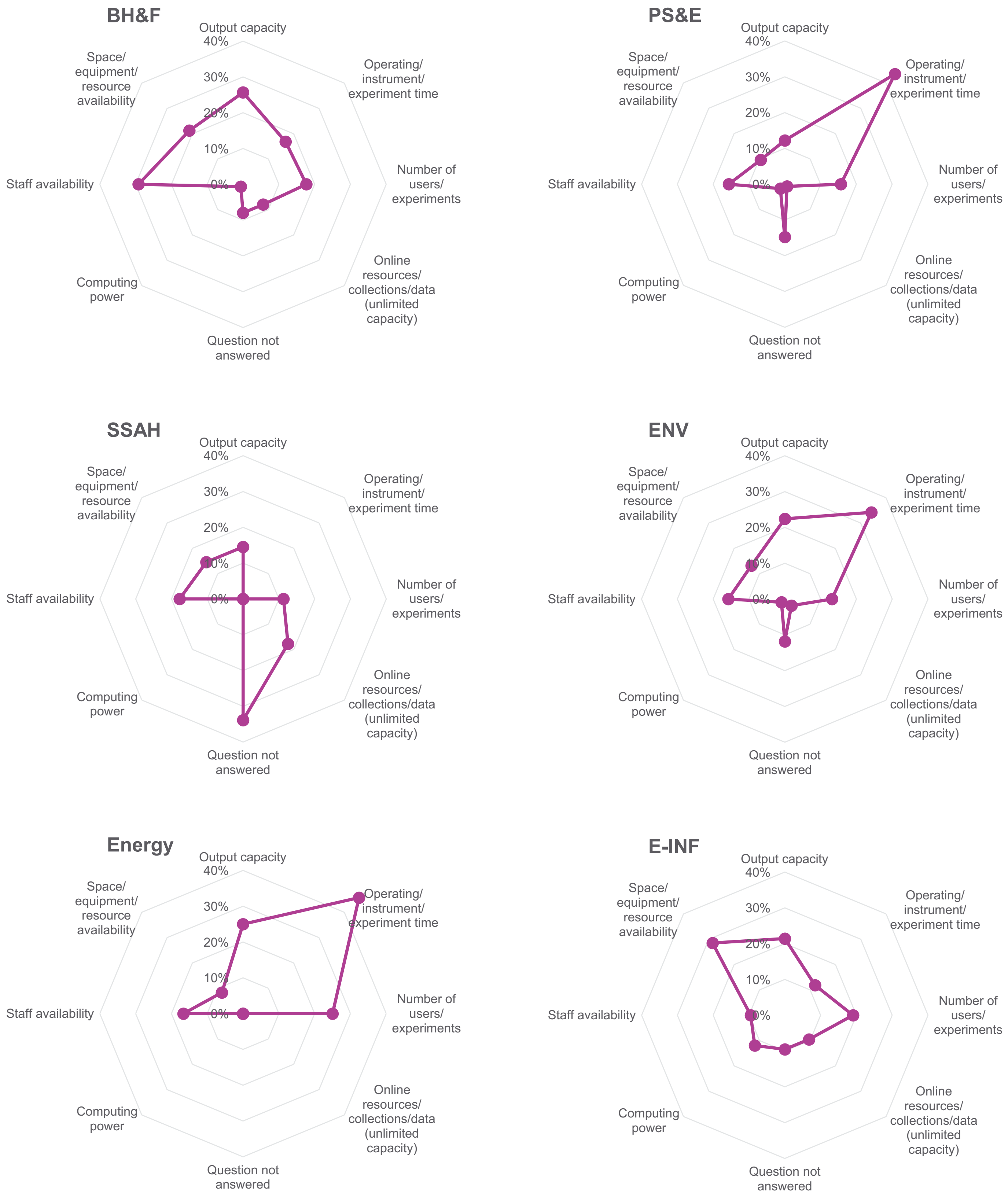


Figure 7.3. How infrastructures measure capacity. Some infrastructures described capacity in multiple ways, so percentages do not sum to 100%.

7.3 Managing capacity

Almost no infrastructure can run at 100% capacity for 100% of the time. We asked infrastructures to describe their aimed capacity levels, i.e. the level they aim to run at. Aimed capacity can be thought of as a percentage of the maximum theoretical capacity of the infrastructure. The theoretical maximum capacity is not always feasible or desired particularly when considering infrastructure management over a long time period. Many infrastructures require blocks of downtime for maintenance or upgrades (e.g. an engineering facility) or must always run non-output processes in the background (e.g. monitoring and accounting processes running on a high performance computing (HPC) machine).

Spare capacity can be thought of as the difference between aimed capacity and the level that an infrastructure is running at. For example, a facility may aim to run for 200 days per year. If it averages running for 137 days a year, its spare capacity would be 63/200 days or 31.5%. Our analysis of spare capacity has some caveats as spare capacity can be difficult to measure. Statistics also may have been inflated by misinterpretation of the different capacity measures asked for in the infrastructure questionnaire.

We examined the 157 infrastructures that began operating before 2016 which provided figures for capacity. Over half of these were operating at their aimed capacity and just under half had some spare capacity. The likelihood of having spare capacity varied according to how capacity was measured and by sector (Figure 7.4). For example, 59% of infrastructures that measured capacity by ‘up-time’ had spare capacity, whilst 29% of infrastructures that used staffing as a measure did.

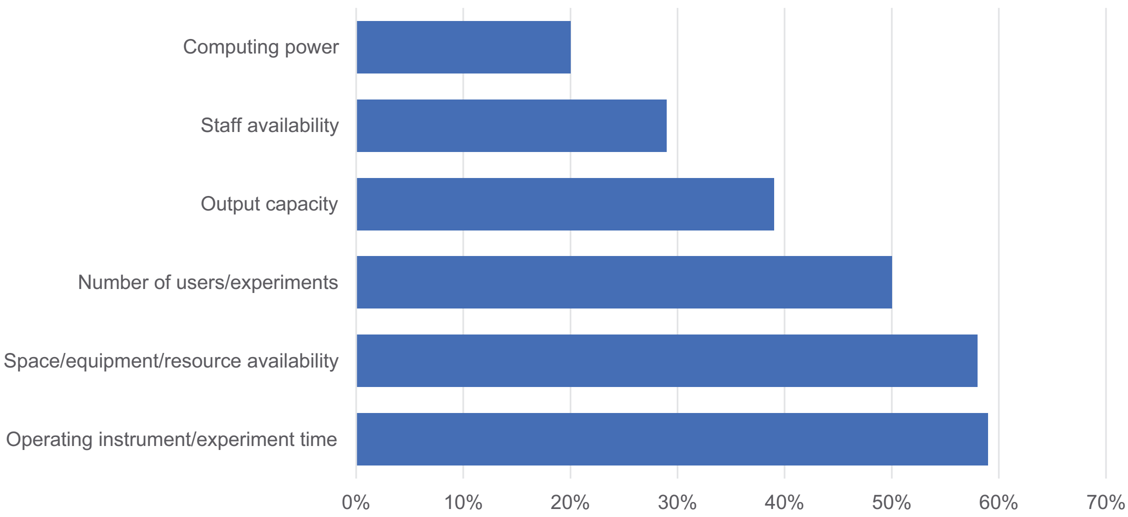


Figure 7.4. Percentage of infrastructures with spare capacity based on capacity measure.

Case study:
The Large Hadron Collider

The LHC at CERN is the world's largest and most powerful particle accelerator. To keep the accelerator operating safely, effectively and reliably, it is shut down over the winter months for maintenance and upgrades. Furthermore, every four to five years the accelerator experiences a long shutdown that can last over two years. These shutdowns are essential for ensuring the LHC operates at its optimum and is developed to continuously support ground-breaking science.

CERN

The case of the LHC demonstrates the trade-off between making full use of an infrastructure in the short run and sustaining and maximising its potential in the long run. For good reasons many infrastructures do not aim to operate all of the time.

There are many possible reasons for spare capacity. Infrastructures that are operational but still developing (e.g. adding new capabilities) may be in a ramping-up phase. It can take time for infrastructures to increase operational levels to aimed capacity or fully exploit new resources. Evidence for spare capacity due to ramping up includes almost twice as many infrastructures operating since 2012 having spare capacity compared to older infrastructures. Additionally, 75% of infrastructures with spare capacity observed increased demand for physical access within the last ten years.

Spare capacity can also be due to genuine lack of demand, for example if there is over-supply. As infrastructures age, technological advances and the emergence of substitute infrastructures could cause demand to decrease. In these cases we would expect to see a decline in demand alongside reports of spare capacity. Overall, only five of the 157 infrastructures (3%) with spare capacity reported that demand for their infrastructure had declined within the last ten years.

Case study:
The Material and Chemical Characterisation facility (MC²)

MC² at the University of Bath incorporates services for nuclear magnetic resonance (NMR), mass spectrometry, X-ray diffraction, thermal/elemental/surface analysis, dynamic reaction monitoring, electron microscopy, bio-imaging and cell analysis, on scales ranging from the molecular to the organism level. The infrastructure measures capacity in terms of accessible hours of operation and aims to operate at 75% capacity (variable by instrument). The remaining 25% of instrument time is set aside for instrument set-up, method development, maintenance, staff/user training and outreach activities.

University of Bath

Whilst MC² aims to operate at an average of 75% capacity across all of the instrumentation, it will operate below this for some. The level of use varies markedly between instruments, depending on its purpose, with some instruments operating optimally at 30% capacity allowing for near-real-time access and analysis, e.g. open access NMR systems, whilst other instruments are used at ~90% capacity for experiments which can be scheduled several months in advance. This emphasises important reasons for spare capacity – the availability to accommodate urgent work, as well as a more responsive service for the community of users where needed, e.g. in reaction monitoring.

7.4 Barriers to performance

The majority of the barriers to performance identified were common across all sectors. Figure 7.5 clusters responses under the main themes. The most frequently mentioned concerns were around funding followed by shortages of personnel and shortage of key skills, which were often interlinked. Retention of key people, particularly digital/data/technical skill-sets was a recurring barrier. Many respondents linked this to the short-term nature of funding, meaning it was only possible to offer short-term contracts, which are less attractive when more competitive salaries are available in the private sector.

- **Funding issues.** In addition to comments on the level of funding, many responses flagged the short-term nature of funding, and the uncertainty this brings, as a critical barrier with implications for operation and staff recruitment/retention. Others cited the need for 'batteries to be included' and were concerned about the complexity of the landscape. Some were grappling with the recent changes to the funding landscape and how to react to different funding structures. Many raised concerns about the implications of exiting the EU exit for funding – particularly those in internationally significant infrastructures
- **Personnel and skills shortages.** Often tied to needs for operational funding, there were notable mentions of a shortage of data science and analytical skills and software engineers across responses, regardless of sector. The challenge of short-term contracts was also mentioned
- **Data related challenges.** The most frequently raised issue was that of access to and sharing of data
- **Managing complex partnerships.** This tended to be cited mostly by those involved in multi-country or multi-funder infrastructures
- **Other barriers** referenced included a range of operational or technical issues specific to the type of infrastructure, challenges associated with inter- and multidisciplinary working, government controls and regulatory barriers, competition with other infrastructures (including private sector) and a range of cultural issues within organisations, within academia or linking to business

Respondents were also asked about how these barriers might change over the mid-term. Responses were largely the same with stability of funding (including worries over the short-term, unpredictable nature of funding) and staffing-related issues cited most frequently. However, the emphasis shifted slightly with greater mentions of building capability within the infrastructure, including barriers to staff succession planning (attraction/retention concerns), worries about maintaining excellence in the face of competition (internationally, from other infrastructures and the private sector), ability to build the user community and how to increase capacity to engage business users.

There were also increased mentions of uncertainty over how the economy will evolve, impact of new technologies and how the research environment itself will change with a 'lack of strategy' as a concern. Issues relating to the management and use of data continued to be raised but with a greater emphasis on potential future restrictions to access, standards and public trust.

Infrastructures also indicated how they were mitigating these risks. This included:

- Seeking to diversify funding streams
- A range of strategies to manage succession problems, to increase the attractiveness of roles and bring young talent into the infrastructures. These often focused on continuous programmes of recruitment, use of apprenticeships, seeking better recognition of technical staff and development of other non-pay offers
- Putting resource into internal and externally available training programmes
- Actively seeking to work with a range of partners to form collaborations and share risks, costs and technical/capacity challenges (i.e. academic and private collaborations)
- Proactive work to raise awareness of the infrastructure capability and support growth of user communities
- Engagement with government and other parties in relation to broader concerns beyond the remit of the infrastructure, such as data access regulation

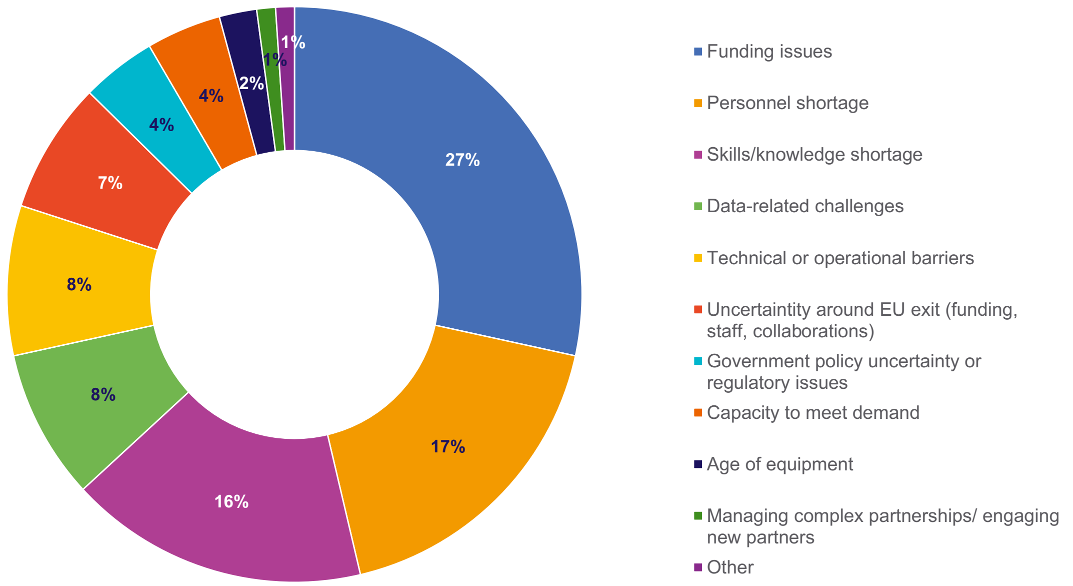


Figure 7.5. Barriers and concerns cited by infrastructures.

Case study:
Foundries, a fertile training ground

University of Edinburgh

One of the hallmarks of the synthetic biology community has been its drive towards greater democracy among both participants and beneficiaries. This extends to skills and training but whilst we are addressing the gap at graduate level and beyond, there remains a pressing shortage of appropriately trained technicians.

National facilities such as Edinburgh's Genome Foundry, one of the largest automated genome assembly platforms in the UK, are an invaluable training ground for early-career researchers in state-of-the-art techniques. Alongside the development and delivery of a wide variety of genome assembly projects – from natural product biosynthesis to gene therapy – the foundry has hosted many guests, from both academic and industrial labs, all keen to better understand the role of automation in synthetic biology.

The UK Centre for Mammalian Synthetic Biology, based at the University of Edinburgh, has started to address the gap in entry-level skills and technicians by hiring school-leavers as modern apprentices in its specialist research facilities. The apprentices work in the lab while gaining formal qualifications as a lab technician through day release to Fife College. After completing his training, the centre's first apprentice, Scott Neilson, began work in the Edinburgh Genome Foundry. There he has become indispensable, acquiring 'green fingers' in operating and maintaining the highly sophisticated platform for DNA assembly. Scott is currently working towards a Higher National Diploma and potentially, in the future, a part-time degree. He has also proved to be an adept instructor and shares his newly-gained expertise with foundry customers.

Chapter 8: Links to the economy

8.1 Working with businesses

Over three quarters of infrastructures reported that they conducted some work with UK businesses and 18% stated that all or most work was directly with UK businesses (Figure 8.1). The energy, PS&E and computational and e-infrastructure sectors reported the highest figures for engagement. However, the interpretation of the question may have varied by sector. In the SSAH sector working with businesses in the classical sense is less common but working with government to inform public policy is common (applying to 75% of infrastructures).

A third of infrastructures have a balanced portfolio of activities across discovery and commercialisation research (Figure 8.2). Across sectors, energy had the greatest proportion of its work commercially focused (25%), considerably above the other sectors, which ranged from 3-10%.

The knowledge and innovation roles of infrastructures make important contributions across the economy. We asked infrastructures to select the economic sectors that they contribute to from a list of forty economic sector categories based on grouped Standard Industrial Classification divisions[20] (see Annex B for details). Research and education were the top sectors identified which is to be expected given their role in generating new knowledge and their association with HEIs. The top ten other economic sectors selected are shown in Table 8.1. Twenty-eight economic sectors were selected by eighty or more infrastructures, and all of the forty economic sector categories were each identified by at least fifteen infrastructures, demonstrating the broad economic and societal impact generated by infrastructures.

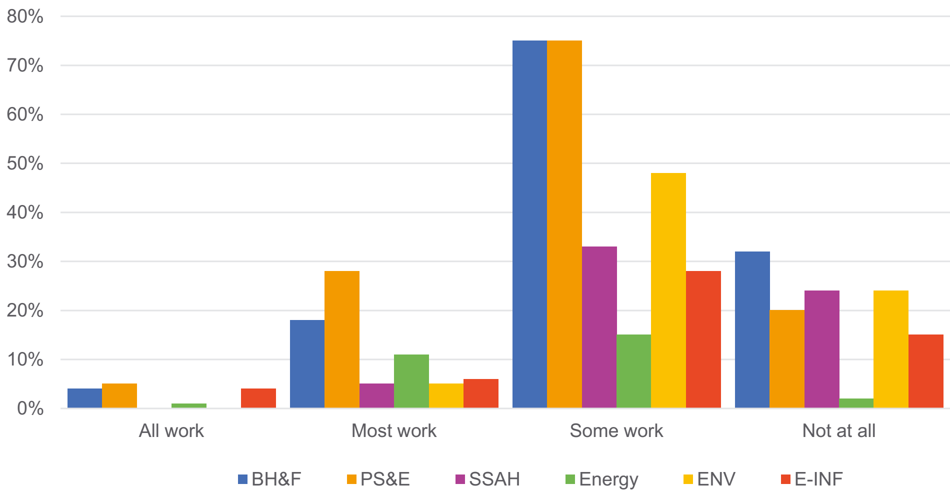


Figure 8.1. Extent to which infrastructures work with UK businesses.

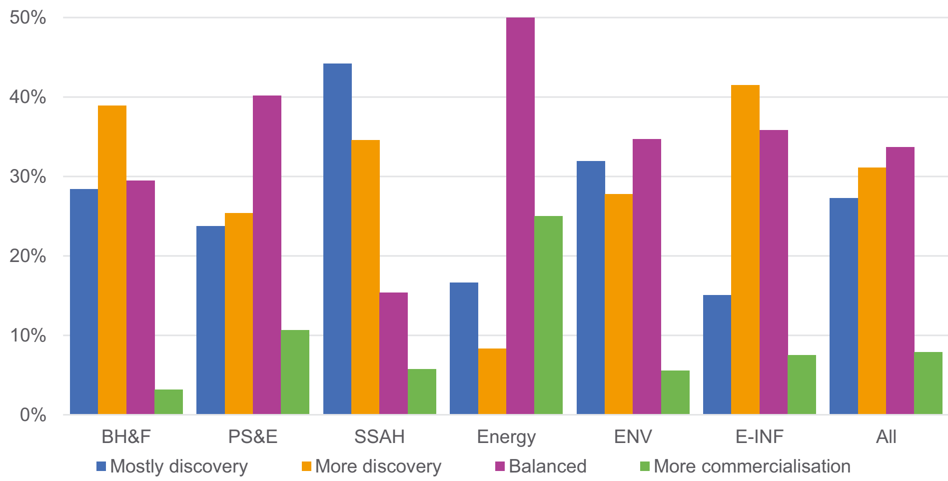


Figure 8.2. Work at infrastructures on a discovery-to-commercialisation spectrum.

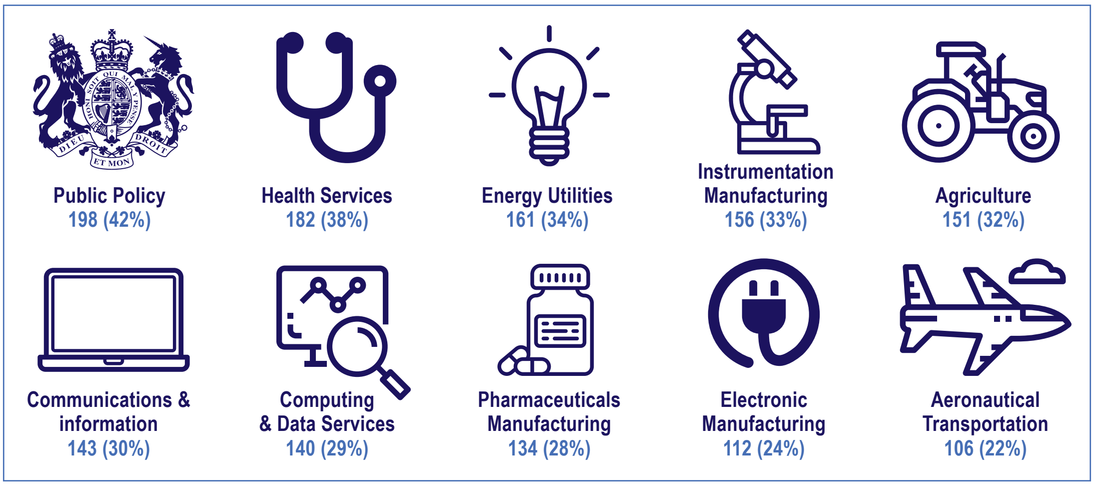


Figure 8.3. Top 10 economic sectors that research and innovation infrastructure see themselves contributing to or working with (excluding research and education).

Research and innovation infrastructures located in close proximity can have had a ‘clustering’ effect, fostering innovation and increasing links with industry. Examples of an infrastructure cluster could include a campus such as the Babraham Research campus, a university consortium such as the N8 research partnership, or a science park such as Culham Science Park which hosts Culham Centre for Fusion Energy.

Clusters around research and innovation infrastructures can have many benefits, including to the local economy, increased skills and jobs to a region and attracting talent for academia and industry. A cluster can create an ‘innovation ecosystem’ within a region, thus accelerating the development of technology and the commercialisation of projects.

Case study: Proximity to drive innovation: the Cambridge Biomedical Campus

The Cambridge Biomedical Campus brings together world-leading discovery science alongside infrastructures, clinical research, teaching hospitals and pharmaceutical and biotechnology companies to create a vibrant clinical research community at the forefront of discovery science and medicine. This campus provides an unparalleled patient-centred approach to research by working alongside NHS and clinical scientists and partners to effectively plan and manage clinical trials.

The initial campus dates to 1962 when the new Addenbrooke’s Hospital and the Medical Research Council (MRC) Laboratory for Molecular Biology (LMB) relocated. A new vision to build a patient-centric research community comprising academics, clinicians and business was announced in 1999. The first phase expanded the campus to house, among others, the global headquarters for AstraZeneca, the University of Cambridge School of Clinical Medicine and the new LMB building which opened in 2013. The LMB has made revolutionary contributions to science such as pioneering the sequencing of DNA and the development of monoclonal antibodies. Twelve Nobel Prizes have been awarded for work carried out by LMB scientists.

Clustering infrastructures with clinical facilities, businesses and research and innovation institutions brings people together to accelerate innovation as well as providing access to technology platforms and equipment. This innovative environment supports teaching, discovery research, patient care and commercial R&D in close proximity, allowing ideas to be discussed and progressed and successful results to be translated into tangible benefits for patients more efficiently.

Case study:
V&A collections inspire the development of sustainable fibres

The Business of Fashion, Textiles and Technology Creative R&D Partnership is one of nine clusters (plus one policy and evidence centre) to be funded under the multi-million pound Creative Industries Clusters Programme. Led by London College of Fashion, University of the Arts London, the five-year project will focus on delivering innovation within the entire fashion and textile supply chain, with special attention given to positioning industry as agents of new technology and materials development.

Victoria and Albert Museum

Drawing on the V&A's rich collection of historical textiles and dress, V&A curators and textiles conservators will be working with colleagues from London College of Fashion, University of the Arts London, and the School of Design, Leeds University on one particular project. This project will use nineteenth century dye books, recipes, records of the animal and waste product collections, historical fibres and textiles as a starting point for developing new, sustainably sourced and produced fibres and composite materials.

A recent exhibition at the V&A entitled Fashioned from Nature focused on production methods and raw materials, as well as their effect on communities and the natural environment. It showcased examples of pioneering 'alternative fibres' manufactured in Europe in the nineteenth and early twentieth century, using materials such as spun glass, pineapple leaf fibre and other organic and waste materials, which might provide pointers to creating a more sustainable fashion industry today.

The aim of this programme[21] is to foster a new, creative business culture in which fashion, textile and technology enterprises, from SMEs to multinational companies, can use R&D as a route to growth. Special attention will be placed on positioning industry as agents of research and development into new materials, technology and sustainable business practices.

Chapter 9: Biological sciences, health and food sector

Gerd Altmann from Pixabay

Research and innovation in the biological sciences, health and food sector uses an array of world-class infrastructures and capabilities to understand the complexities of form, function and interactions within and between organisms and to translate these discoveries for societal and economic benefit. The life sciences community explores fundamental scientific questions by utilising complex experimental approaches that generate vast amounts of data, often from high-throughput approaches and by applying these data for the improvement of health, agriculture, the environment and society at large. As the complexity of approaches has increased and advances in technology have accelerated, so has the need to work within and across traditional disciplinary boundaries. Scientists across different fields, from clinicians to engineers and from biologists to social scientists, are converging to solve the present and future problems to which our society is, or will be, exposed.

Within the UK, there are many stakeholders supporting the delivery of life science research. Within UK Research and Innovation much of this is covered by the remits of the Biotechnology and Biological Sciences Research Council (BBSRC) and the MRC. In addition, this area is supported by other public sector organisations, industry and the third sector, including:

- The NHS and other health-related governmental bodies (e.g. Public Health England)
- Devolved Administrations (e.g. Northern Ireland invests heavily in food safety, Scotland in animal phenotyping, Wales in agriculture and imaging)
- Clinical infrastructures supported by UK health departments, for example the National Institute for Health Research (NIHR)[22] funded through the DHSC
- Biomedical research charities[23]
- Industrial/commercial partners who support innovation and research (e.g. Syngenta)
- Farms and agricultural networks (e.g. The Roslin Institute collaborates with farmers to perform research/collect data on their land)

The UK is well connected with European infrastructures and is a partner in six of the sixteen Health and Food Research Infrastructures supported by ESFRI[24].

9.1 Current landscape

Infrastructures in the BH&F sector include data banks, biological tissue banks and other collections of biological samples, integrated clusters of small research facilities, high-capacity/throughput technology, high-cost cutting-edge analytical infrastructure, high-fidelity imaging technology, facilities for animal and plant housing, breeding and phenotyping, networks of computing infrastructures, databases and research cohorts of volunteers. Of the 751 infrastructures with a regional, national or international scope, 244 reported their primary domain as the BH&F sector. In addition, 53% of other respondents highlighted that their infrastructures had relevant links to the BH&F sector (Figure 9.1). This high level of linkage emphasises the engagement and involvement of scientists from the physical, engineering, computational, mathematical and social sciences in tackling research challenges across the life sciences community and the importance of challenges in the life sciences forming part of the aims of a wide range of infrastructures.

Accordingly, the suite of infrastructures in the BH&F sector are diverse in nature and are comprised of different types of facilities and capabilities. They include:

- **Knowledge-based resources**, such as UK Biobank[26], which is a national and international health resource that provides researchers with access to clinical and biomedical information on 500,000 volunteers to improve the prevention, diagnosis and treatment of serious human diseases
- **Distributed, major multi-user capabilities** such as ELIXIR, the pan-European research infrastructure for biological information, comprising a hub and national Nodes with twenty-two members from twenty-one countries. The UK hosts the ELIXIR hub at the Wellcome Genome Campus and has a UK national node comprising fifteen UK-based organisations

- **Networks** of cutting-edge precision equipment, such as those established through the Clinical Research Capabilities and Technology Initiative[27], in close proximity to clinical investigation and care facilities in order to advance clinical research
- **National centres** addressing research areas of national significance, for example supporting farming and agriculture, or supporting wellbeing through the development of the annual influenza vaccine. Examples include the World Influenza Centre at the Francis Crick Institute[28] and the national and international reference laboratories for viral diseases at The Pirbright Institute[29]

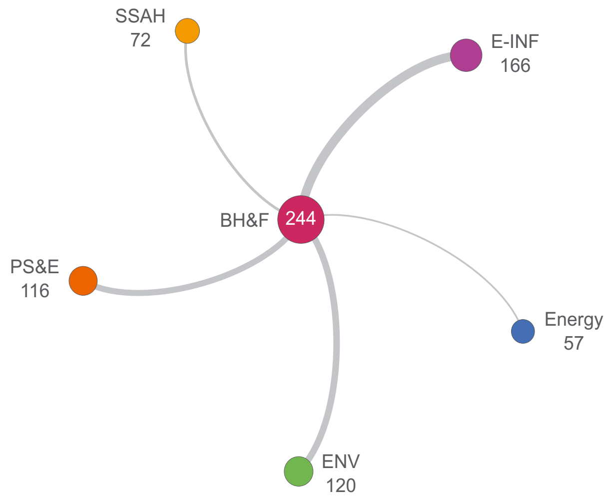


Figure 9.1. Overlap (co-occurrence) of research and innovation infrastructures between the biological sciences, health and food infrastructures sector and other sectors. The sizes relate to the proportion of infrastructures that overlap (co-occurrence) based on the number of responses that selected each sector. There are strong interdependencies with the computational and e-infrastructure, physical sciences and engineering and environment sectors. Acknowledgement: Sci2Team[25].

Figure 9.2. Breadth and overlap of sub-disciplines in biological sciences, health and food sector. The size of the nodes relates to the number of infrastructures that selected each sub-discipline. Acknowledgement: Sci2Team[25]

Figure 9.2 illustrates the breadth and overlap of BH&F sub-disciplines that are supported by infrastructures across the UK, from crop science and agriculture through to target validation for drug discovery. The sub-disciplines (represented by coloured circles) are based on the categories used by the Research Councils' grants submission system.

Case study: Cohort data infrastructures

Some of the UK's oldest infrastructures are longstanding data collections, e.g. the 1936 Lothian Birth Cohort. The UK houses many unique, historical population data sets which will grow in historical significance over time. To ensure these data can be reused in future years, they need to be curated to remain accessible as technology changes.

The large volume of population data being generated in modern studies and the increasing need to link and integrate complex data to support their interpretation resulted in a new informatics research institute, The Farr Institute, being established in 2012 and a new successor institute, Health Data Research UK, being incorporated in 2017. These investments will support the interrogation of traditional clinical, biological, population and environmental data and also data from emerging data forms for public benefit, e.g. wearable technology.

Case Study: Rothamsted Research

Rothamsted Research

Rothamsted is the longest running agricultural research institution in the world. It is home to the Long-Term Experiments – the oldest continuous agronomic (field) experiments in the world – which started between 1843 and 1856 and are still running to this day. These historic field experiments continue to serve as an invaluable infrastructure and scientific data resource, which remains relevant due to careful management and application of new methods. They includes the Broadbalk Winter Wheat Experiment, which has been investigating ways of improving the yield of winter wheat through inorganic fertilisers and different organic manures since 1843, providing a unique data set (containing, for example, 172 years of wheat grain and straw yield data and sixty-nine years of weed survey data) and resulting in the publication of nearly 600 papers.

Case Study: The National Virology Centre

UKRI

The centre is located at The Pirbright Institute (formerly the Institute of Animal Health), which has been in existence for over 100 years. It was initially established as a cattle testing station for tuberculosis and now houses the infrastructure for one of the UK's leading virus diagnostics and surveillance centres. At the forefront of international virus research, the site has been recently redeveloped to incorporate a state-of-the-art high-containment (Specified Animal Pathogen Order Group 4) laboratory, home to the BBSRC National Virology Centre which uses an innovative gasket system, negative pressure and extensive high efficiency particulate arrestance (HEPA) air filters to prevent air escaping the building. The facility enables scientists to research dangerous pathogens and combat zoonotic diseases that can spread from animals to humans (e.g. flu), highly contagious livestock viruses (e.g. bluetongue in sheep, Marek's disease in chickens) and future viral threats (e.g. African swine fever virus).

The infrastructures that responded to the questionnaires were largely UK Research and Innovation funded/part-funded projects but also included a number of clinical research infrastructures, funded through other means, e.g. the DHSC. The UK has a rich clinical infrastructure, e.g. a network of biomedical research centres, bio-resources and clinical research facilities, which is more extensive than the presented data indicate.

Many UK infrastructures are funded through competitive processes. They are awarded funds based on research strengths so tend to be located close to the academic user base. The link to universities was highlighted in the questionnaire with 88% of infrastructures being housed within another legal entity (e.g. university or bespoke research institute). Of these, 71% were considered a long-term facility or resource and the remaining 17% were reported as being dependent upon short-term external funding (Figure 9.3).

Infrastructures in the BH&F sector are long-term investments (Figure 9.4). Almost 20% of BH&F infrastructures have been operational for over twenty-five years with 10% having exceeded forty years. Although Figure 9.4 suggests a large increase in new infrastructures in recent years, the data do not illustrate the complex picture regarding the lifecycle of infrastructures, such as the level of turnover of existing infrastructures, the repurposing/re-development of longstanding facilities, or the rise of new infrastructures to support and maximise previous investments.

Over three quarters of infrastructures expect that their operational lifespan will exceed fifteen years and the majority of these expect this to be over twenty-five years. The difficulty in securing long-term operational funding is borne out by the disparity in the data between the envisaged life-span of an infrastructure and the time horizon for which an infrastructure is confident to plan ahead. Nearly two thirds of respondents were unable to plan over three years in advance and fewer than 10% could confidently plan beyond a six-year horizon. This will have implications for both strategic planning and the overall efficiencies that could be achieved with greater certainty of funding.

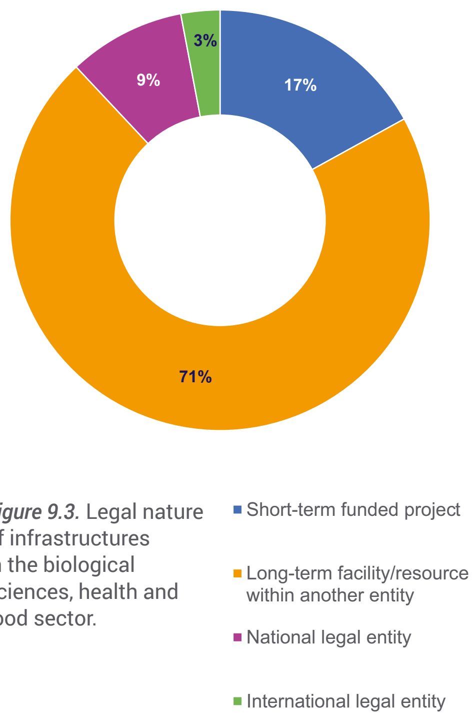


Figure 9.3. Legal nature of infrastructures in the biological sciences, health and food sector.

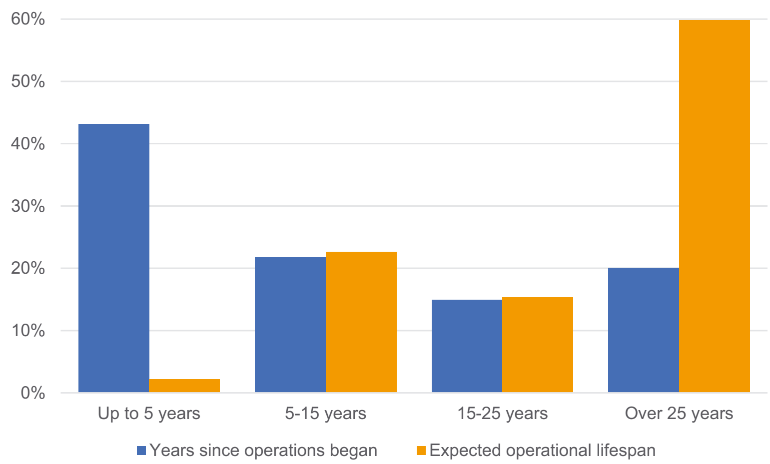


Figure 9.4. Number of infrastructures grouped according to the number of years since operations began and their expected operational lifespan.

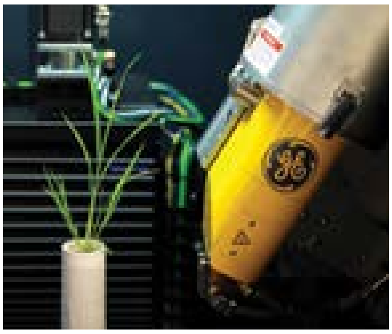
Almost a quarter of infrastructures supporting the BH&F sector are distributed (comprised of multi-site facilities) or virtual (e.g. accessed digitally) (Figure 9.5). With these, the highest cost often is not in the initial construction but in the long-term recurring costs required for running, maintaining and replacing/updating facilities.

The future spread and nature of infrastructures may alter as scientific research shifts. Until relatively recently, research has largely been delivered through individual research groups each with access to their own local equipment and facilities. However, there is an increasing shift towards holistic approaches more reliant on large distributed teams with common access to infrastructure, via a multi-user regional or national platform. This change in approach is highlighted by the increasing number of ESFRI infrastructures that the UK is a member of.

Collaboration is 'business as usual', with 92% of infrastructures reporting that they collaborate with other organisations. Of these, 80% collaborate both nationally and internationally. Overseas users are attracted to UK infrastructures for a variety of reasons (Figure 9.6), including the need to collaborate, the uniqueness of infrastructures housed here and co-location with complementary facilities, e.g. access to clinical or agri-tech facilities. The majority of BH&F infrastructures (61%) also provide resources or related services to the wider community, beyond the infrastructure itself.

Case study: EMPHASIS and UK plant and crop phenotyping

The European Infrastructure for Multiscale Plant Phenomics and Simulation (EMPHASIS) is a pan-European distributed research infrastructure on plant and crop phenotyping. It is a collaboration involving twenty-four countries and is a project of the ESFRI roadmap. EMPHASIS will address research questions aimed at improving crop resilience through in-depth understanding of crop performance and physiology in real-world environments, by enabling access to a suite of pan-European facilities in relevant geographical/climatic zones. UK infrastructure relevant in addressing such challenges includes:



University of Nottingham

- The Institute for Sustainable Food (University of Sheffield) which offers next-generation climate control, analytical and plant disease phenotyping facilities across disciplines to enable discoveries and deliver real-world solutions to achieve food security
- The Hounsfield Facility (University of Nottingham) which is a multidisciplinary research centre employing state-of-the-art imaging techniques, such as X-Ray computed tomography and laser ablation tomography, to understand plant and soil interactions and their responses to environmental stresses
- The national phenotyping network PhenomUK which will enable coordination at a UK level. This will build on new advances in fundamental engineering and physical sciences, bringing the necessary disciplines into closer contact and promoting an integrated, holistic view of plant and crop phenotyping across the UK

University of Sheffield

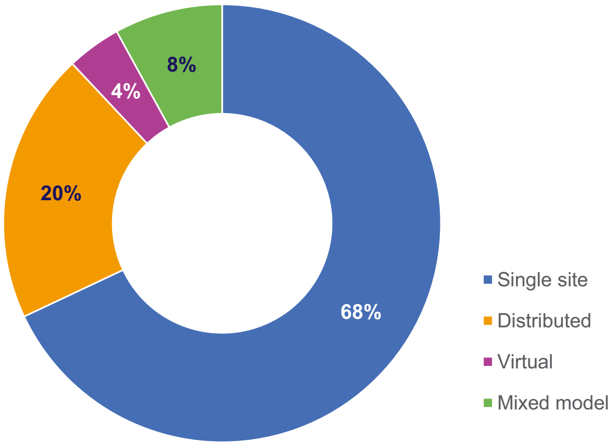


Figure 9.5. Distribution of infrastructures according to whether they are single-sited, distributed, virtual, or have a mixed model of more than one of these options.

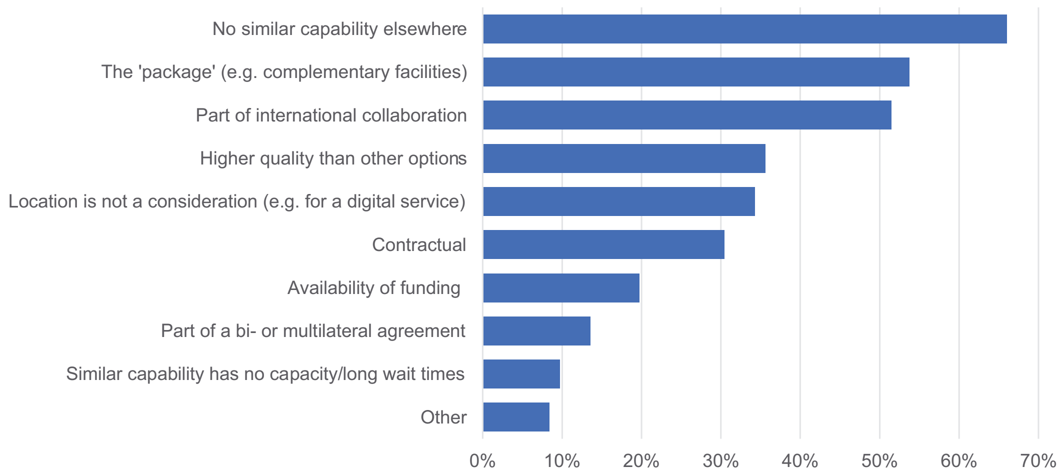


Figure 9.6. Reasons given for attracting international users to biological sciences, health and food infrastructures. Options were not mutually exclusive and respondents could select as many as were applicable.

9.2 Interdependency with e-infrastructure

'Big data' was once the purview of astronomers and high-energy physicists. However, the advent of new high-resolution imaging modalities, the increasing use of automated, high-throughput approaches in 'omics and the advances in phenotyping have led to increasing collections of complex, multi-modal biological data that require an agile e-infrastructure environment to support them.

E-infrastructure underpins the majority of BH&F infrastructures, with 73% having a significant e-infrastructure and/or data requirement or component. Most BH&F infrastructures (82%) consider that e-infrastructure and data will increase in importance for their infrastructure over the next five to ten years. This highlights the increasing challenge for the research community in analysing, integrating, managing and deriving new knowledge from the huge volume of data.

The BH&F community is starting to harness the opportunities to utilise data-led approaches such as artificial intelligence (AI) to gain deeper insights into fields such as oncology, understanding the rules of life, e.g. through linking genotype to phenotype, investigating the effects of environment on both genotype and phenotype and improving the sustainability and resilience of agriculture. In addition, the desire to virtually link population-level data (e.g. health and routine administrative data) with patient-level data to allow a comprehensive view of public health (e.g. Data Linkage Scotland[30]) will lead to additional data and e-infrastructure requirements.

At the international scale, the European Bioinformatics Institute (EBI)[31] based near Cambridge is part of the European Molecular Biology Laboratory (EMBL)[32] and is a world leader in bioinformatics data resource provision and the centre of global efforts to analyse, store and disseminate biological data. The data resources hosted at EMBL-EBI are critically important for life-science academic and commercial research, receiving over thirty-eight million web requests per day. The EBI also hosts a number of key national and international data infrastructures such as the hub of ELIXIR and Open Targets, a successful large-scale industrial collaboration in pre-competitive drug discovery.

9.3 Engagement with the wider economy

The top eight sectors of the economy beyond research and education that benefit from access either directly to BH&F infrastructures or through the scientific outputs they support are shown in Figure 9.7. Some of the top sectors supported are health services, agriculture, the pharmaceutical industry and the food industry. There are also strong links to public policy.

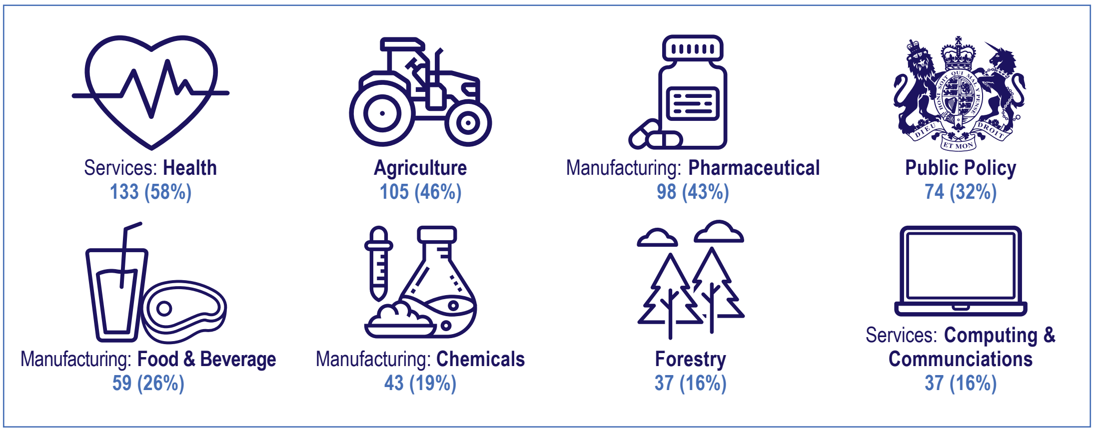
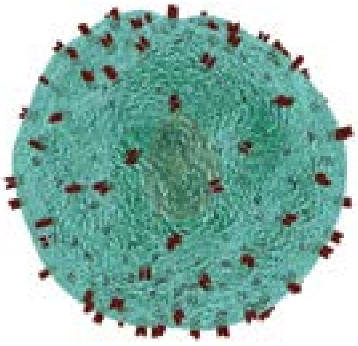


Figure 9.7. Top eight economic sectors to which biological sciences, health and food infrastructures contribute to or work with, excluding research and education.

Case study:
Accelerating therapeutic discovery: Cell therapies

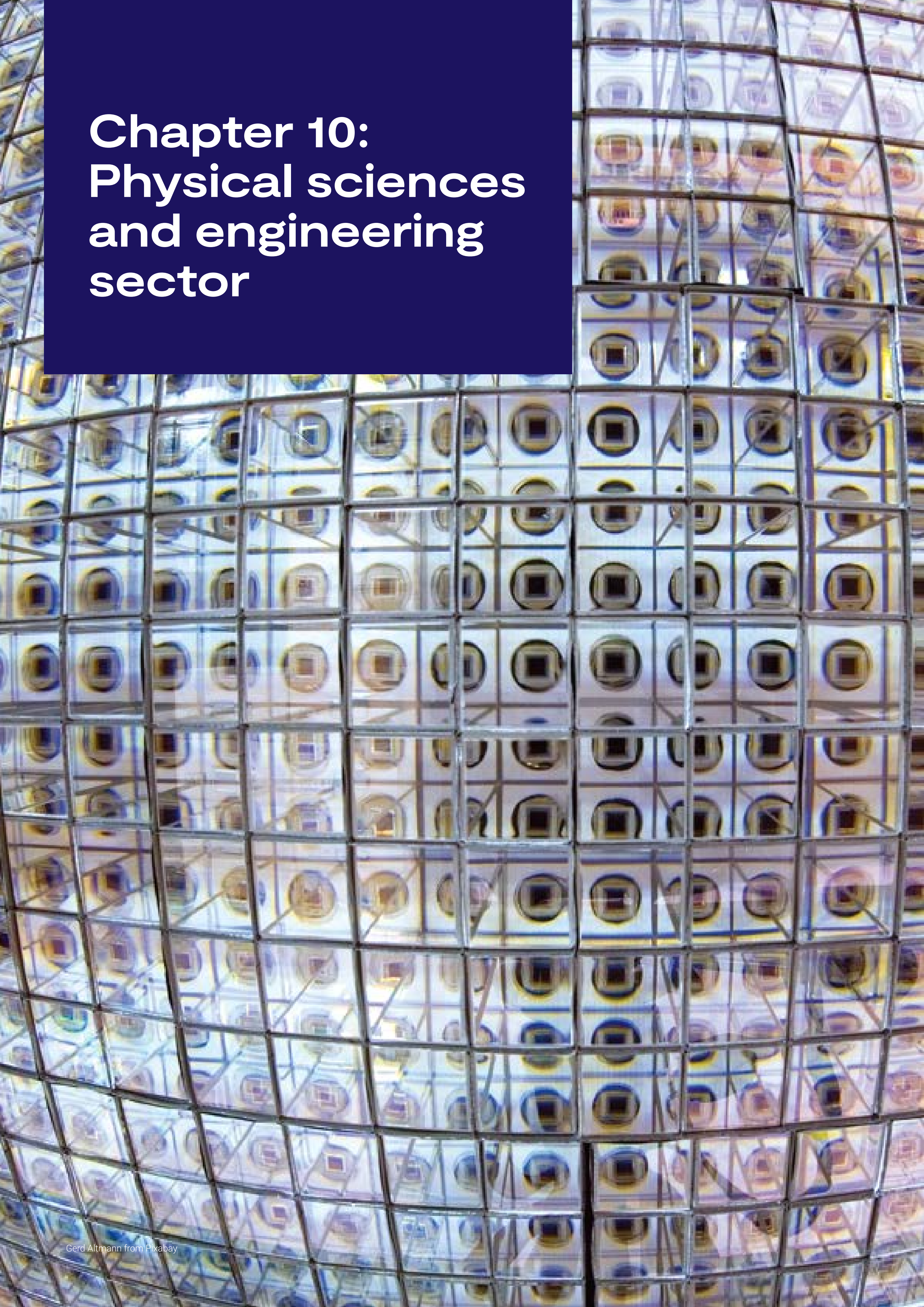
Translation is a long-term process relying on the pull-through of discovery science into new products. Autolus Ltd, a biopharmaceutical company focused on the development and commercialisation of next-generation engineered T-cell therapies for haematological and solid tumours, became the first company to enter the Cell and Gene Therapy Catapult's manufacturing centre in Stevenage. Autolus is a University College London spin-out company, built on ten years of BBSRC and MRC funding and translated further through the NIHR Biomedical Research Centre at University College London Hospital.



Most research within the BH&F sector is towards discovery science (64%). The majority of infrastructures in the BH&F sector have some engagement with industry as 76% of infrastructures reported doing 'some', 'most' or 'all' of their work with UK businesses. Only 4% of infrastructures' output focuses primarily on commercialisation, though 33% conduct a 'balanced' portfolio of research and innovation.

Engagement with the commercial sector is more evident in some of the large, independent research partnership projects or those set up with innovation or translation as a key goal. For example, the MRC/AstraZeneca Centre for Lead Discovery allows academic researchers access to industry infrastructure, e.g. high throughput robotic drug-screening capabilities to support discovery and development of small molecule therapeutics. Another vehicle for supporting the pull-through of discovery science to industry is via engines such as the Cell and Gene Therapy Catapult, which helps to translate research excellence into commercially successful businesses for the UK. An additional approach is taken by the five BBSRC Research and Innovation Campuses where each campus is centred on a critical mass of world-leading bioscience providing a unique environment where fledgling bioscience-based companies can access specialist facilities and exchange ideas with leading researchers, creating a low-risk environment for high-risk innovation. The campuses focus on areas ranging from the agri-tech industry through to medical biotechnology.

Chapter 10: Physical sciences and engineering sector



Gerd Altmann from Pixabay

The physical sciences and engineering research and innovation spectrum spans all branches of physics, chemistry, mathematics, materials, information and computing technology, quantum technologies, healthcare technologies, engineering and manufacturing.

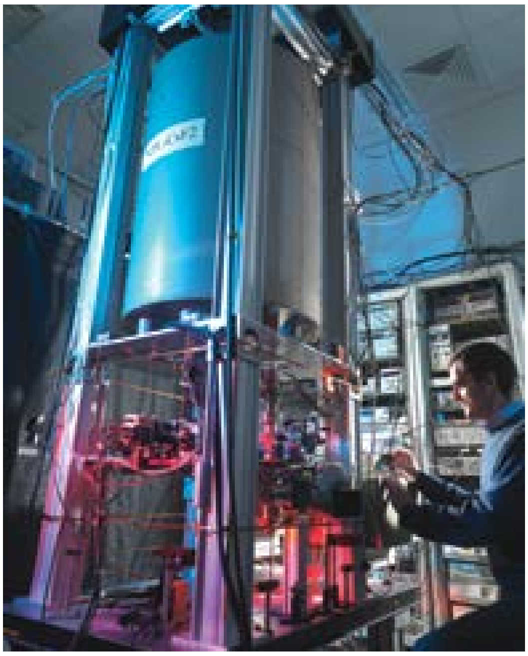
Because of the breadth of research being carried out across PS&E, the supporting infrastructures are also naturally broad in their nature, including specialised large-scale equipment, facilities, institutions and observatories. These infrastructures incorporate capabilities ranging from lasers and accelerators to mass spectrometry, NMR and imaging. This broad range of capability is essential to developing new and more sophisticated technologies that can revolutionise research and innovation across all sectors.

Physical sciences and engineering infrastructures have enabled some of the most important discoveries and advances of the twenty-first century. In 2012 the Higgs boson was observed almost fifty years after its existence was first theorised at the LHC at CERN. Using technologies developed in the sector, cryo-electron microscopy (cryo-EM) has been evolved and the UK now hosts a national user facility for the study of biological structures from the molecular to the cellular level. Graphene was first isolated by researchers at the University of Manchester working on an instrument development project. The unique properties of the material mean it could have a vast array of practical applications including the creation of new materials and the manufacture of innovative electronics. The Nobel Prize for Physics in 2010 was awarded to Professors Geim and Novoselov from Manchester for their ground-breaking work which is now being taken forward at the National Graphene Institute.

Case study: National Physical Laboratory (NPL) infrastructures

NPL is the UK's national measurement institute. It provides measurement capability to UK scientists and businesses through 380 state-of-the-art laboratories, with regional centres located across the UK providing local access to facilities and expertise. NPL delivers solutions to some of the UK's biggest challenges and opportunities in advanced manufacturing, health, energy, environment and digital technologies.

Atomic Time developed by NPL in the 1950s now serves a huge industry of digital and location-based services from GPS and mobile phones to banking transactions and high-frequency trading. In the future more accurate and resilient time from NPL will support automatous-vehicles safety, quantum technology commercialisation and the delivery of new energy supplies.



NPL's Caesium Fountain, the primary reference for time. Credit: NPL

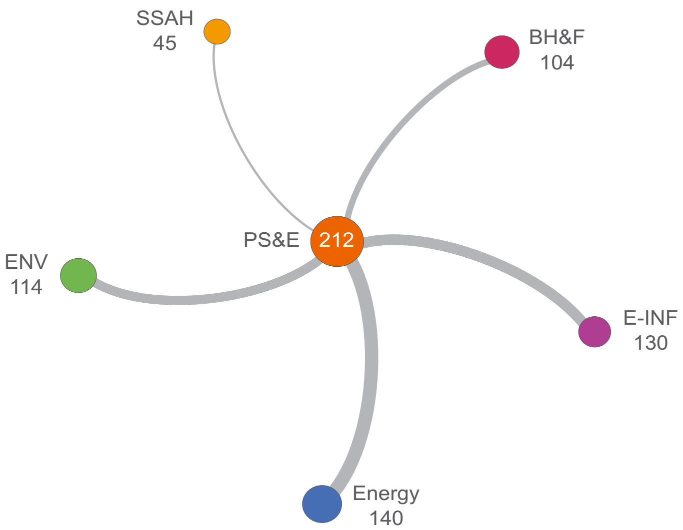
10.1 The current landscape

Over a quarter (27%) of infrastructures that responded to the UK Research and Innovation questionnaire named PS&E as their primary domain, while also supporting science from across all other sectors. Figure 10.1 highlights the strength of overlap between infrastructures in the PS&E sector (central circle) and the other sectors. There are strong interdependencies across the BH&F, environment and energy sectors.

One common approach to infrastructure in the PS&E sector is co-location in campuses, which bring together an ecosystem of infrastructures to deliver complex capabilities. The Harwell and Daresbury campuses co-locate high-tech companies alongside the national multi-sector facilities, fostering collaboration and innovation.

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 Engineering and Physical Sciences Research Council (EPSRC) National Research Facilities. These support strategic resources of national importance to provide leading-edge capabilities and technique development at a national level.

However, the majority of PS&E infrastructures are single site, focused capabilities, typically housed within another legal entity such as a university. A significant number of capabilities are spread across the globe (e.g. the Japan Proton Accelerator Research Complex and the Large-aperture Synoptic Survey Telescope, currently under construction in Chile) and some infrastructures are even based in space (e.g. the International Space Station). As well as these single infrastructures, there are also co-located facilities with multiple infrastructures such as suites of telescopes (e.g. ESO) or detectors (e.g. the Jefferson Lab) and multiple capabilities, such as the National Physical Laboratory infrastructures.



The PS&E sector is centrally placed and the peripheral nodes represent the other sectors. The sizes relate to the proportion of infrastructures that overlap with the PS&E sector (co-occurrence) based on the number of responses that selected each sector.

Figure 10.1. Overlap between infrastructures with a primary affinity to the physical sciences and engineering sector and the other sectors. Acknowledgement: Sci2Team[25].

Case study:
Space-based telescopes

The James Webb Space Telescope (JWST) will be the biggest space telescope ever built. Designed and built by NASA in partnership with the Canadian and European Space Agencies, it is due for launch in 2021. The JWST will orbit in deep space, 1.5 million km from Earth, on a mission of at least five years.

As the successor to the Hubble Space Telescope, the JWST is expected to produce even more astounding images of the Universe. The telescope will be able to explore the distant Universe and the evolution of planets, stars and galaxies as never before. It will look back in time to 400 million years after the Big Bang, allowing us to see the first objects that formed as the Universe cooled. The UK led the European consortium to build the Mid InfraRed Instrument (MIRI) for the JWST and was also responsible for the overall construction of the instrument and the quality control to ensure that MIRI will operate as intended and cope with the harsh conditions of space.

A key attribute of infrastructure within PS&E is its longevity. There are a high number of infrastructures with an expected lifespan of over twenty-five years, reflecting the size, complexity and physical nature of the infrastructures typical of this sector. A number of the larger, longer-running infrastructures are also multidisciplinary in nature, as showcased in Chapter 2.2. Although the sector contains a large proportion of these long-running infrastructures, there is also continual growth and investment in new research capabilities. Since 2015 a number of new institutes hosting significant infrastructure have been supported. These include The Alan Turing Institute in data science, the Faraday Institution in battery science and technology, the Henry Royce Institute in advanced materials, the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) and most recently, the Rosalind Franklin Institute, focused on transforming life science through interdisciplinary research and technology development.

Given the long lifetimes of many PS&E infrastructures, there is a need to factor-in continuous technical advancements throughout their lifecycles. These advancements ensure the infrastructures are able to remain fit for purpose, such as being able to handle increasingly large data sets, dealing with challenging/extreme environments and coping with the need for greater technical and analytical expertise to maximise the scientific outputs.

Physical sciences and engineering infrastructures, such as the LHC at CERN, have faced some of the most extreme 'big data' challenges, and with infrastructures generating ever greater volumes of data, the reliance on e-infrastructure facilities and expertise is expected to increase over time. Seventy per cent of PS&E infrastructures envisage e-infrastructure and data becoming more relevant to their infrastructures in the next five to ten years.

10.2 Characterising the sector

Physical sciences and engineering infrastructures can be characterised as either capability- and discovery-driven, application-driven or challenge-driven infrastructures to describe the science and innovation they tend to support (Figure 10.2). In many cases the different infrastructures provide complementary expertise to each other. To answer complex, interdisciplinary problems, a combination of approaches making use of infrastructures across the different categories is required, hence the importance of this interconnectivity.

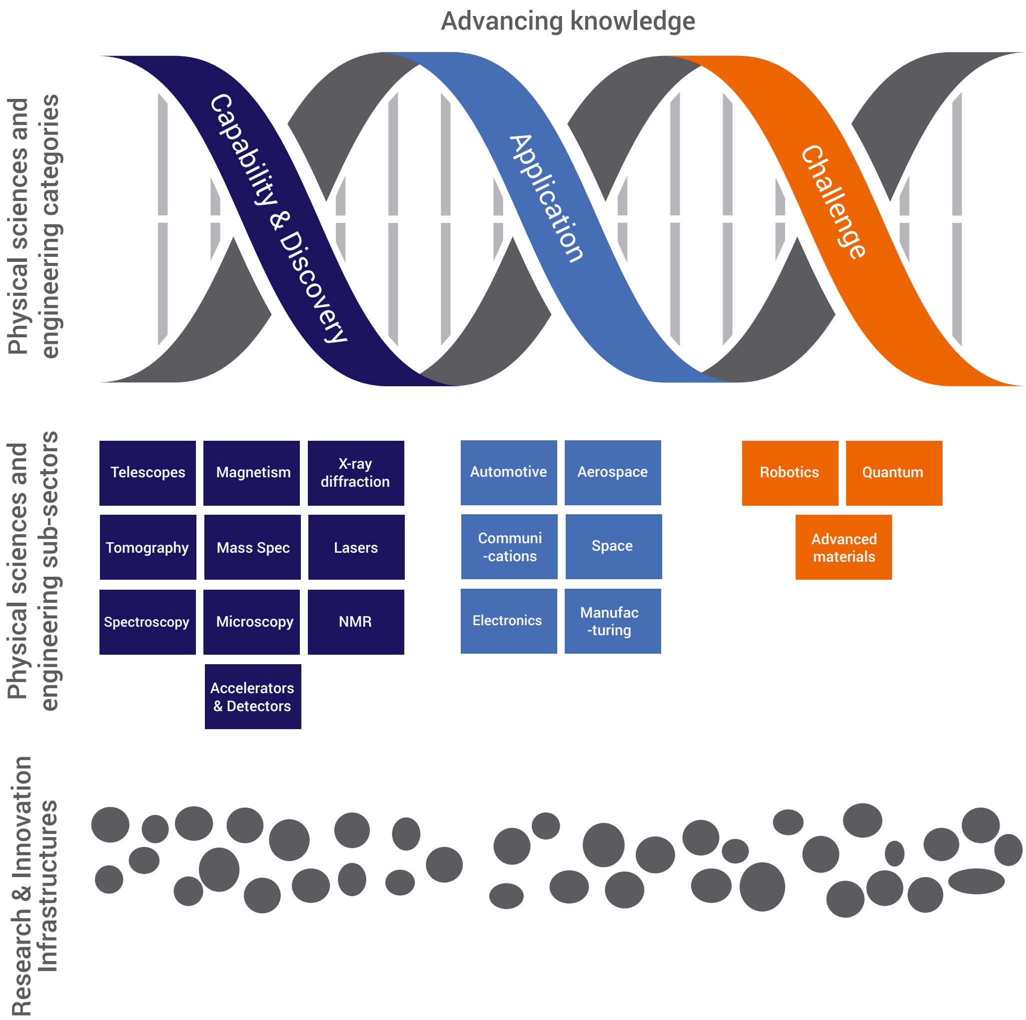


Figure 10.2. Classification and sub-sector grouping of the physical sciences and engineering research and innovation infrastructures.

Capability and Discovery driven infrastructure:
Infrastructure of this kind provides the essential capability that allows us to design, model, synthesise, characterise and test materials at different length scales (from atomic scale through to components) and to enable discovery. It include large-scale, campus-based facilities as well as distributed and often internationally-based state-of-the-art infrastructures and major university-based clusters of capability.

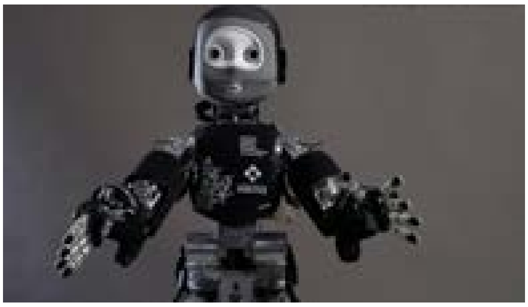
CERN

The LHC at CERN, the world's largest and most powerful particle accelerator, is helping scientists understand the fundamental laws of nature and, for example, enabled the discovery of the Higgs boson particle that proved how particles gain mass.

Application driven infrastructure:
These infrastructures have an identifiable relevance to industrial sectors or end-user groups within the economy such as aerospace, automotive and space. The complexity of the user problems will often require these infrastructures to be used in concert with other infrastructures.

National Epitaxy Facility

The National Epitaxy Facility supports world-class semiconductor research in the UK, providing a range of semiconductor materials and devices to academics and industrial customers.



Edinburgh Centre for Robotics

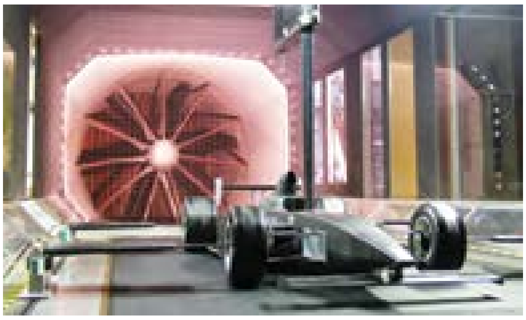
Challenge driven infrastructure:
These infrastructures tend to be part of wider initiatives targeted towards addressing major scientific, technical, innovation, societal or policy challenges for which additional government funding has been committed. They often build on outstanding, existing capability which has been built up over many years through capability-driven investments.

For example, the National Robotarium will expand on existing facilities to create a unique, world-leading centre for the practical application of robotics and autonomous systems in areas as diverse as healthcare, manufacturing and hazardous environments.

Case study:
National Wind Tunnel Facility

An investment of £14.5M in 2015 developed and upgraded a suite of seventeen national wind tunnel facilities (NWTF). The investment is aimed at keeping the UK at the forefront of aerodynamic and fluid mechanics research. Infrastructure is available to all UK-based researchers and aims to create nodes of excellence attracting young researchers. The NWTF also aims to establish a closer tie with industry, creating a pull-through environment and an intended spill-over of the collaboration and benefits to other sectors.

Bringing the seventeen facilities together to provide a service that is greater than the sum of its individual tunnels has allowed a model to develop that provides strategic oversight and management of facilities in a shared manner. It also ensures a collaborative, aligned approach.



National Wind Tunnel Facility

10.3 The importance of international collaboration

Research in this sector increasingly relies on sophisticated experiments at a range of bespoke national and international facilities, often at the leading edge of what is technically possible. Due to the scale and costs of such facilities many infrastructures can only be realised through international collaborations and long-term strategic planning. This is very typical of the capability-driven infrastructures that provide insights into the fundamental building blocks of matter or the origin and development of the Universe, such as the Facility for AntiProton and Ion Research in Europe (FAIR) currently being built in Germany. For this reason, the PS&E sector has the largest proportion of infrastructures located outside the UK.

10.4 Impacts

Physical sciences and engineering infrastructures support a diversity of economic sectors beyond research and education (Figure 10.3). With one exception, each of the forty economic sector choices was selected by at least one PS&E infrastructure. Physical sciences and engineering infrastructures are particularly important to the manufacturing and transportation economic sectors. Close links with industry across the PS&E sector are reflected by the fact that 86% of PS&E infrastructures perform at least some work that is directly informed by businesses.

The impacts of the science and utilisation of technologies developed within the PS&E sector are extreme, influencing our everyday lives. The Compact Linac at Daresbury Laboratory has been developed to investigate the potential for small, low-energy linear accelerators to be utilised in areas such as security and wastewater treatment. Research by Bristol Robotics Laboratory in the field of ground-breaking robotic systems enables surgeons to put joint fractures back together using a minimally invasive approach.

Infrastructures can have impacts on our fundamental understanding of the Universe around us, helping us to answer questions that we are only just beginning to contemplate. For example, UK scientists and engineers played key roles in the construction and operation of the Laser Interferometer Gravitational-Wave Observatory (LIGO), which runs two detectors in the USA, and the Virgo gravitational-wave detector in Italy.

After the first detection of gravitational waves in 2016, LIGO and Virgo recently detected gravitational waves from what appears to be a collision between two neutron stars about 500 million light years from Earth. Neutron stars are the dense remnants of massive exploded stars. Just one day later, the network registered another event about 1.2 billion light-years away; initial analysis suggests it might have been the collision of a neutron star and black hole.

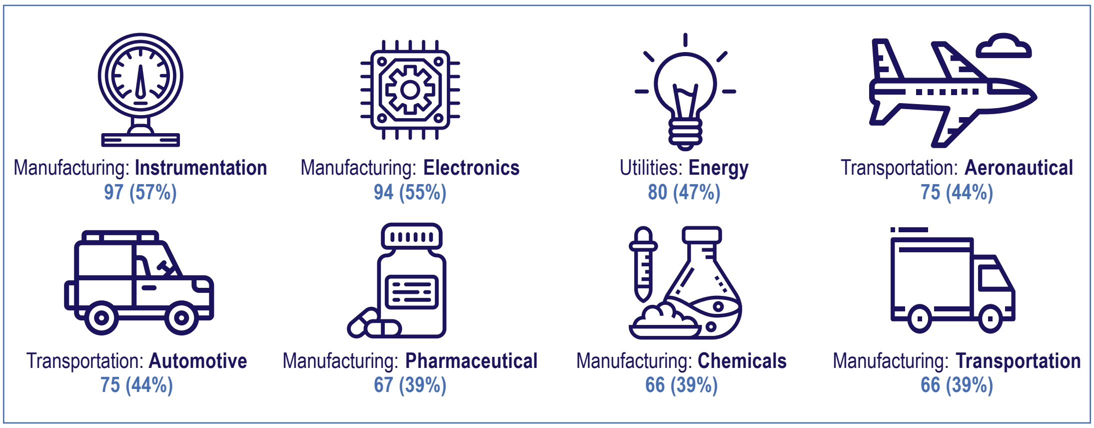
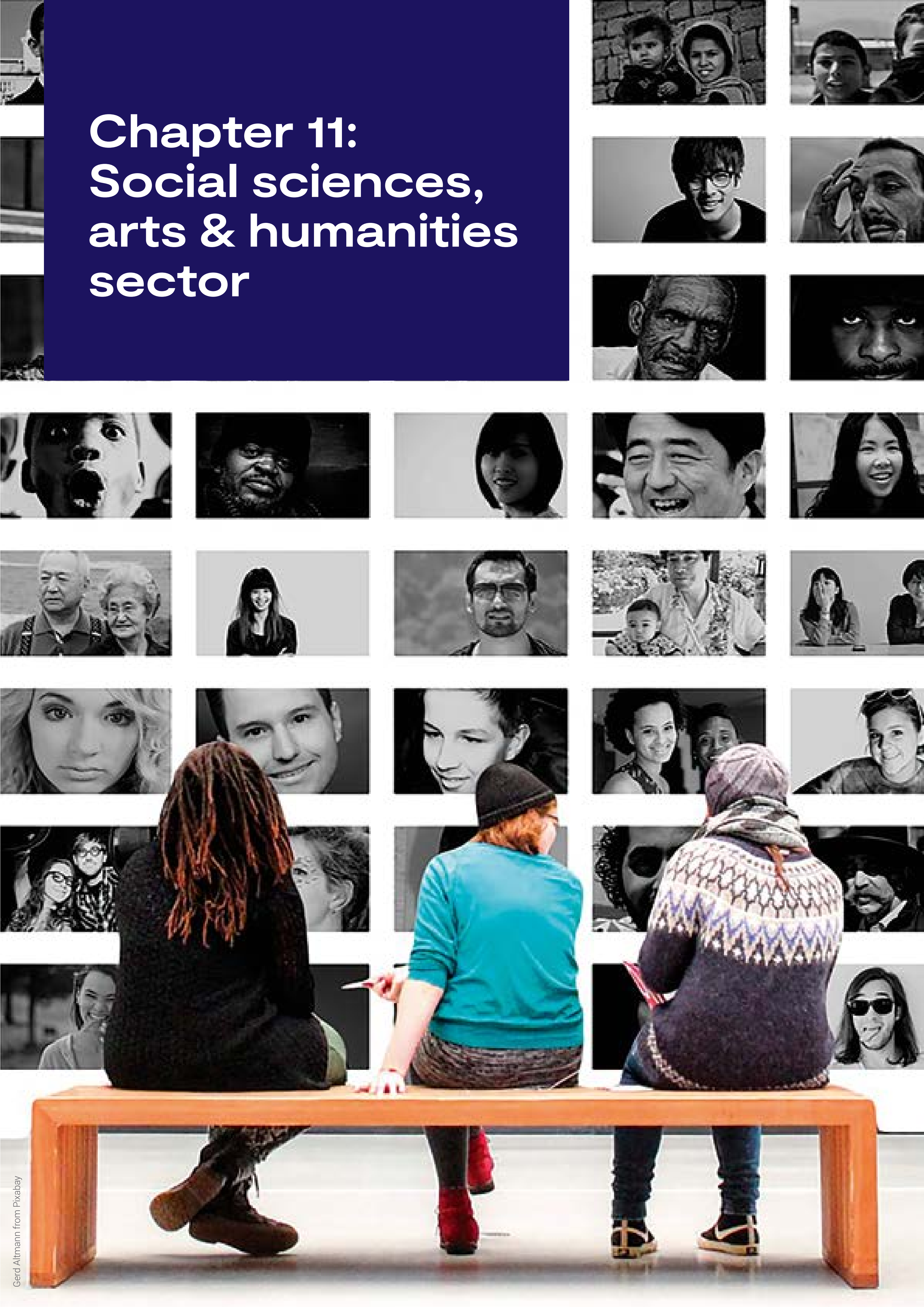


Figure 10.3. Top eight economic sectors to which physical sciences and engineering infrastructures contribute to or work with.

Chapter 11: Social sciences, arts & humanities sector



Gerd Altmann from Pixabay

Infrastructures in the social sciences, arts and humanities sector are used by researchers from a broad range of disciplines. Social sciences, arts and humanities infrastructures are also used extensively by policy-makers across government, by the third sector and by the wider public. They are globally visible as examples of the UK's leading role in research and innovation and a high proportion engage with business.

Social sciences, arts and humanities infrastructures include tools and techniques such as clusters of expert capability and provision of hardware or facilities. Many infrastructures collect or facilitate access to research objects, including physical resources such as historic artefacts and virtual resources such as social science data. Other distinguishing features of the SSAH infrastructures include large user bases, diversified and short-term funding models and dispersal across multiple locations. Social sciences, arts and humanities infrastructures are characterised by discipline agnosticism. Among respondents, 95% of infrastructures involve multiple subdisciplines of SSAH and 69% report relevance to sectors beyond SSAH.

Of 751 respondents to the questionnaire, 110 infrastructures identified SSAH as their primary sector. Of these, 107 are based in the UK. Respondents included a mixture of targeted and self-identified infrastructures. Some disciplines within SSAH are less familiar with using the term 'infrastructure' to describe what they offer and may have been slower to engage compared to other sectors.

11.1 Form and function of infrastructures

In this sector, 95% of infrastructures have a presence at a physical location, 49% of infrastructures are single-sited and 16% are dispersed (Figure 11.1). Overall, 73% of infrastructures responding offer some level of virtual access, but only 5% identify as entirely 'virtual' or digital in nature. In some cases, infrastructures are closely linked. For instance, sensitive data resources benefit from other infrastructures for collection, storage, analysis and facilitating researcher access, while being infrastructures themselves.

Broadly, SSAH infrastructures operate across a spectrum, ranging from primarily service delivery that is dependent on expert human resource, to hardware and facilities provision. Some infrastructures have a mixed model. The UKDS, for instance, has secure facilities for data storage and user facilities and offers advice services.

For many SSAH infrastructures the presence of specialists embedded within the infrastructure for activities such as processing research data or curating historic artefacts, or providing training or advice, is a key and essential part of the infrastructure. Maintaining and developing sufficient expert capability is an ongoing challenge. These infrastructures' purpose can be to build capability amongst researchers, or amongst research data or output users from government or the third sector. Some infrastructures exist to enhance the use of resources or organisations that are infrastructures themselves. The Cohort & Longitudinal Studies Enhancement Resources (CLOSER) and the National Museums Collection Centre are examples of this.

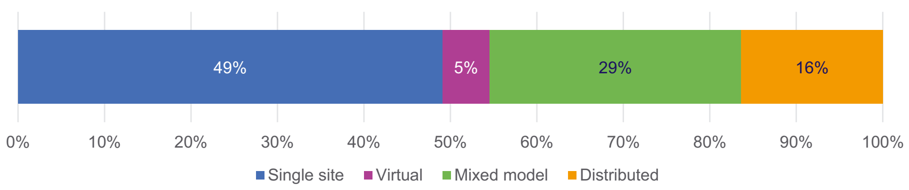


Figure 11.1. Type of social sciences, arts and humanities infrastructures.

Case study:
CLOSER's informs recommendations on early years intervention

CLOSER is a collaboration of UK social and biomedical longitudinal studies, the British Library and the UKDS, funded by the Economic and Social Research Council (ESRC) and the MRC. There are currently eight studies in the CLOSER partnership, comprising four national and three regional birth cohort studies and Understanding Society (the UK Household Longitudinal Study).

In 2018, CLOSER submitted evidence to the House of Commons Science and Technology Committee: Evidence-based Early Years intervention, on the contribution of the UK's longitudinal studies as leading sources of evidence on how early circumstances and experiences affect people's lives from childhood to adulthood[33]. For example, research using the Millennium Cohort Study, 1958 National Child Development Study, 1970 British Cohort Study and Understanding Society, has shown how factors such as mother's health during pregnancy, child's birthweight, parents' education and employment and family housing and socio-economic circumstances can have a lasting effect on children's cognitive, social and behavioural development. In particular, being born into poverty or disadvantage can have lasting effects on health, education, employment and ageing. CLOSER also highlighted the potential of linking administrative data held by the government to this longitudinal survey data to generate new insights.

This evidence was cited in the committee's report[34] and supported its recommendation to government that academic researchers be enabled to access government administrative data (while ensuring appropriate privacy and safeguarding mechanisms are in place). The government has committed to providing secure access to de-identified data for accredited researchers[35] and is currently working on the development of Administrative Data Research UK (ADR UK). This is supported by a £44 million investment from ESRC and will be set up in collaboration with the Office for National Statistics. ADR UK will provide access to data from government departments, local authorities and health authorities to answer vital research questions on early intervention and childhood adversity.

Many infrastructures in the SSAH domain involve the substantive provision of hardware or facilities. This can include providing secure places such as ‘safe pods’ in university libraries for the analysis of personal data, or tools for user-led digitisation of historic archives. Heritage science (the use of science to understand, manage and communicate the human story expressed through landscape, buildings and artefacts) demands increasingly specialist expertise, instrumentation and laboratory facilities as well as investment in the integration of capability. For museums, research can enable the enhancement of collections and spaces, for instance by developing new curation or visualisation technology or immersive visitor experiences. In some cases, providing researcher access entails trade-offs with other demands, for instance in museum settings where objects and spaces are accessible to a broader, non-researcher audience.

Funding models for SSAH infrastructures are diverse. They include co-funding agreements with major charities, international partnership agreements and quality-related (QR) block funding awarded to host universities. Government departments are significant funders, particularly the DCMS. Thirty-eight per cent of SSAH infrastructures attract non-governmental funding. Arts infrastructures often have highly diversified revenue streams, generating income through commercial and philanthropic activity. This improves the capability of the sector to articulate the purpose and value of infrastructure to a range of audiences. Much of this funding is, however, short-term, with 19% of responding infrastructures funded through ‘soft money’ with no commitment to long-term sustainability. Other business models, such as charging for data access, may conflict with the principle of free and open access.

The SSAH sector is characterised by its infrastructures’ accumulation of value over time. For instance, museum collections facilitate comparative analysis by building increasingly broad and well-documented collections. Longitudinal studies and repeat cross-sectional studies (for instance of elections) also enable increasingly complex insights as more data is added. Social sciences, arts and humanities infrastructures are characterised by their longevity (see also Chapter 3.3). They are some of the oldest and longest-running infrastructures in the UK with 34% originating before 1978 and 79% expecting their infrastructure’s lifespan to exceed twenty-five years. This holds for the many service-orientated infrastructures as well as physical resources (e.g. collections) whose primary functions are delivered through expert capability rather than physical hardware. Longevity also brings challenges such as the need to store, maintain and preserve expanding collections of research objects over the long term.

11.2 Research objects (physical and virtual resources)

In the SSAH sector, 90% of infrastructures create, collect, curate or process research objects as a significant function. These objects are diverse, ranging from unique physical resources such as artefacts to virtual ones like structured data sets for quantitative analysis. Research objects’ provenance also covers a broad spectrum. While some derive from instrumentation, particularly in the heritage science field, a distinguishing feature is the creation of objects through other methods. This can include social surveys collected through fieldwork, consumer data obtained through partnership with business, or objects deposited in museums. Indeed, many SSAH research objects were created for purposes other than research. From archaeological finds to large administrative data sets, their handling creates unique challenges and requirements for embedded expertise. Increasingly, data linkage is enabling infrastructure data to be used in new ways, maximising value and drawing new insights by, e.g. connecting data collected specifically for research with data sets created by government.

There is significant capability across the SSAH infrastructure landscape in the capture, processing and analysis of complex data about people. Complexity can arise for a number of reasons. The collection method, for instance social science surveys, may require careful consideration of representativeness. Data may be personal or sensitive.

In the case of non-research data, such as medieval manuscripts or recent administrative data sets, expert curation may be needed before objects are usable for research. Processing and providing access to such data frequently involves working within legal, ethical and public acceptability frameworks.

The ongoing digitisation of physical collections generates further complex data, such as high-resolution 3D models of objects or XML-encoded texts. Overall, enabling access to complex data, maximising value through curation and linkage and ensuring secure and ethical use are specialisms of the SSAH landscape. Digitisation of research objects offers opportunities for increased access and international cooperation while potentially lowering access costs for users and providers.

Most (86%) SSAH infrastructures also serve other disciplines. This requires deposit protocols, processing standards and access methods, which are discipline- and user-agnostic. It also facilitates the development and application of teaching methods and tools that have value beyond the SSAH sector. For example, trainee surgeons have used textile collections to develop fine motor control, while remote-imaging technology developed for conservation purposes has been used by structural engineers to assess building safety.

Digital technology has changed the way we collect, map and represent physical and virtual resources and 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 AI, concept and entity recognition and virtualisation.

Physical artefacts based in universities, galleries, libraries, archives and museums (GLAMs) and other heritage organisations serve thousands of users and tens of millions of research object requests per year (Figure 11.2). Many of these collections are unique, irreplaceable and increasingly fragile, demanding high levels of skill for access, conservation, interpretation and specialist facilities for storage and analysis. Continuous growth of public research object collections can stem from legal deposit requirements, legislative barriers to object disposal and increased research object production. This creates significant challenges in terms of siting such as increasing storage costs, making it difficult to renew or relocate an infrastructure.

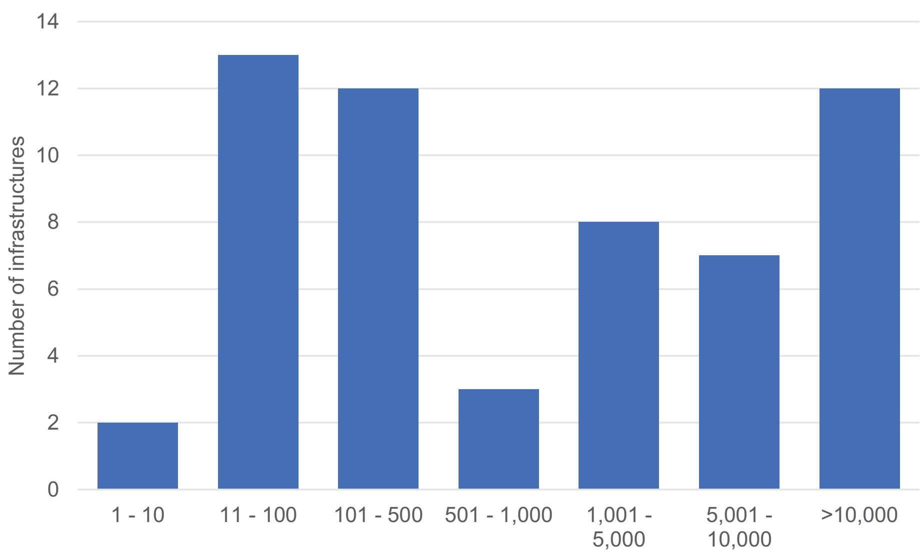


Figure 11.2. Annual numbers of users visiting social sciences, arts and humanities infrastructures.
The distribution is bimodal with one infrastructure peak in the low hundreds and another in the tens of thousands.

11.3 Impacts and outputs

Social sciences, arts and humanities infrastructures contribute extensively to socioeconomic impact, from the development of public policy to directly working with businesses. Over half (57%) of infrastructures work with business (Figure 11.3). Examples of value to business include the provision of attitudes or economic data and creation of, or advice on, ethical or legal frameworks such as copyright law for business activity. Infrastructures that develop research capacity in quantitative social science or heritage science in particular also generate significant value for the labour market. Indeed, private sector demand for such capability creates significant challenges for infrastructures that depend on human expertise for delivery.

Social sciences, arts and humanities infrastructures enable government and business to understand economic drivers and outlooks. Longitudinal data resources have revealed the labour market impacts of vocational education, for instance, while other social science infrastructures have worked with major retailers to understand customer origins. Key areas of engagement with economic sectors outside research and education include the creative industries and recreation (72% of SSAH infrastructures) and public policy broadly (63% of SSAH infrastructures) (Figure 11.4).

Included in the 72% of infrastructures working with creative industries and recreation are world-renowned GLAMs and heritage organisations that are amongst the UK's main visitor attractions, both for local populations and for visitors from abroad, playing a highly significant role in the multi-billion-pound heritage tourist economy. About half of all visitors to the UK cite culture as their reason to visit, with Arts and Humanities Research Council (AHRC) Independent Research Organisations (IROs) accounting for eight of the UK's ten most popular attractions[36]. It is estimated that the national Gross Value Added (GVA) of the heritage economy is £29 billion equating to 2% of the national GVA, with heritage tourism expenditure contributing £16.9 billion.

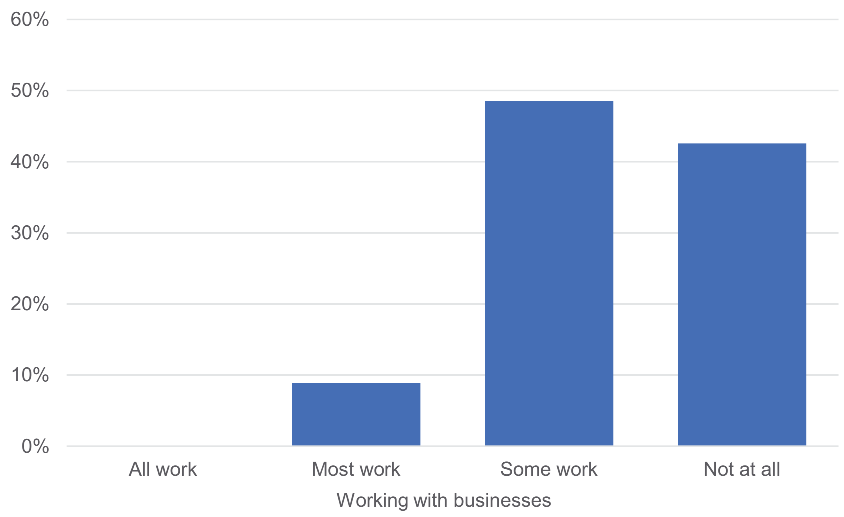
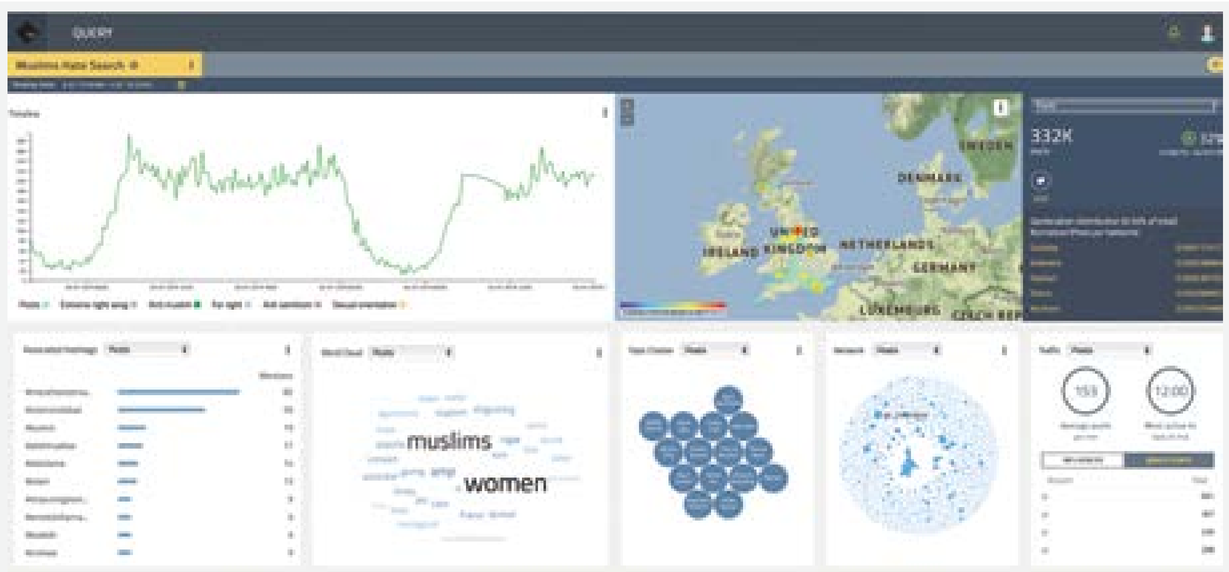


Figure 11.3. Extent to which social sciences, arts and humanities infrastructures directly work with businesses.

Case study:
Using data analysis to support the National Online Hate Crime Hub

HateLab, part of the ESRC-funded Social Data Science Lab, makes use of social media data to investigate hate speech and crime. Researchers at the lab have developed an Online Hate Speech Dashboard[37], in collaboration with the National Online Hate Crime Hub and in consultation with all four police forces in Wales, Greater Manchester Police, the Welsh Government, the government's Behavioural Insights Team and several hate crime charities.

The dashboard tracks trends of online hate speech in real time, by geographical region. This assists analysts to identify areas that require operational and policy attention and allows police and support organisations both to respond more quickly to spikes in hate and to pre-empt the spread of hate speech and crime following 'trigger events'. Crucially it speeds up access to this information in the 'golden hour' after such an event. The Director of the National Online Hate Crime Hub stated that efficiencies created by the dashboard have led to savings of £500,000.



Almost three quarters of infrastructures (72%) reported substantive policy or public service delivery impact. Longitudinal data infrastructures in the social sciences enable influences on health and economic outcomes to be understood across the life course. Linkage of data sets has enabled increasingly powerful analyses in this field, generating considerable additional value from both government data and publicly funded data resources. Other infrastructures, such as the What Works centres, evaluate policy effectiveness or facilitate access to policy-relevant research.

Policy relevance can be relatively specific (for instance, the tax-benefit microsimulation model EUROMOD) or applicable to a range of government research interest areas at national and local level. Administrative data infrastructures offer new opportunities to answer questions of public importance in a timely manner.

11.4 Social sciences, arts and humanities infrastructure users

Apart from direct access, 71% of SSAH infrastructures provide services and resources to a wide community of users. Activities can include advising on the availability and appropriate use of research objects or providing training. Other infrastructures develop methodology or policy on researcher ethics, curation of artefacts or object and materials analysis. Social sciences, arts and humanities infrastructures are characterised by open access and have the highest rate of unrestricted access across sectors (60% of infrastructures). Just 6% require access to be mediated via an internal user.

Heritage organisations and GLAM infrastructures in the humanities serve hundreds of thousands of research users from outside public research organisations each year. The need to facilitate public access on a very extensive scale generates its own challenges in terms of accessibility and discoverability of collections and their maintenance and preservation.

Social sciences, arts and humanities infrastructures are inherently international and 96% have users from outside the UK. Almost half of respondents said that the capability they deliver is globally unique, with 81% noting that they attract international users due to lack of similar capability elsewhere. The sector's infrastructures are highly collaborative (85%) nationally and internationally, attracting investment to the UK. Six infrastructures surveyed, for instance, attract more than 20% of their income from EU funding sources.

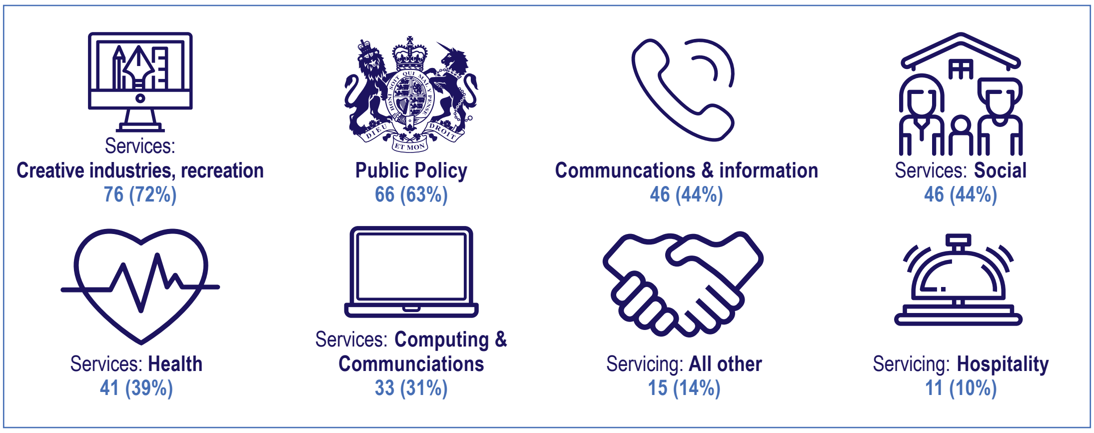


Figure 11.4. Top economic sectors (in addition to research and education) which infrastructures in the social sciences, arts and humanities sector contribute to or work with.

Case study:
The Engine Shed

© Ashley Coombs

Historic Environment Scotland (HES) is an IRO enabling research that provides an unparalleled view of how human activity and intervention has shaped Scotland. Its research infrastructure supports world-class research in a range of fields, including surveying and recording, heritage science and physical and digital archiving.

The Engine Shed is Scotland's dedicated building conservation centre, based in Stirling. Part of HES, it serves as a central hub for building and conservation professionals and the general public. The Engine Shed was established on the premise that Scotland's built heritage holds countless stories – about the people who built it, lived in it and used it – and that knowledge of the past provides pointers to the future. Its in-house experts provide advice to the heritage sector and the public to ensure best practice and help raise standards in conservation of traditional buildings. As part of the Engine Shed's innovative training for practice-based research in conservation, stonemasonry and traditional building materials and methods, augmented reality and 3D printing is used to enable accurate reconstructions. This research also drives a programme of skills-based public engagement with local colleges and schools as part of a wider effort to ensure that 'children of the digital age' remain connected to and confident working with physical materials.

The Engine Shed houses the HES Digital Documentation Team that uses cutting-edge digital technologies to document heritage in 3D to inform the research that underpins sustainable conservation, heritage management, learning and interpretation efforts. The team generates the research data that are used for interactive tours and virtual visits, creating innovative immersive visitor experiences. HES is part of the emerging UK Research Infrastructure for Heritage Science that will drive access to these blended facilities, enhancing scientific research and cross-disciplinary and international collaborations.

Chapter 12: Environment sector

Environmental infrastructure is critical to reach, observe, model, simulate and predict our complex environment, as well as to understand how humans impact and are affected by it, including health and wellbeing. Environmental researchers study the entire planet, from the deep oceans and the centre of the Earth to the edge of the atmosphere and the hostile environments of the polar regions. The sector has a strong track record of discoveries that bring about action, from identifying the hole in the ozone layer to the observations and modelling revealing the risks of climate change. Environmental science is essential to ensure the environment, people and business succeed together in meeting 21st century challenges.

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

Rising to the cutting-edge science challenges of our time and delivering environmental, economic and social solutions to real-world problems demands world-leading infrastructure. We also need to be cognisant of the specialist needs of the environment sector for infrastructure. A characteristic of the environment sector is the breadth of scales from nano to planetary, from seconds to millions of years and the harsh and hazardous environments often encountered. To tackle complex problems and drive scientific progress, we must facilitate whole-system approaches that ensure the UK environment sector leads the world in research and innovation spanning scientific disciplines and borders.

12.1 Characteristics of the landscape

Ninety-four of the infrastructures who responded to the questionnaire identified their primary sector as environment. Between half and three quarters of the remaining 657 infrastructures in the other five sectors also identified environment as a sector their infrastructure covered (Figure 12.1). This demonstrates the breadth and scope of the environment sector and highlights the cross-cutting nature of its infrastructures. For example, 74% of computational and e-infrastructures also identified the environment sector as a secondary domain.

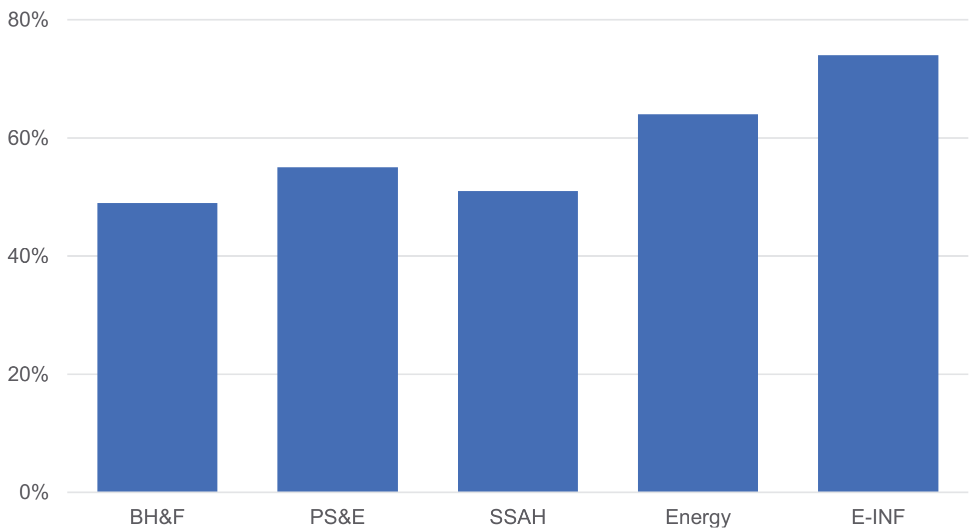


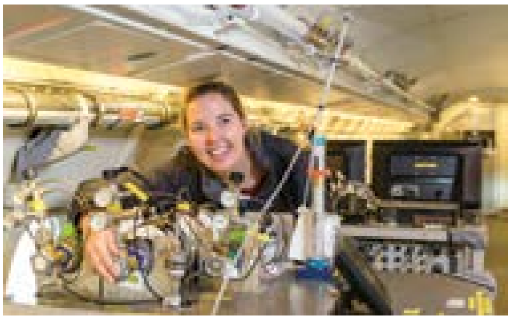
Figure 12.1. Percentage of infrastructures in other primary sectors that identified environment as a secondary sector.

Case study:
From the poles to the skies

The Natural Environment Research Council (NERC) owns several research ships that support complex, multidisciplinary research and include state-of-the-art technology and instruments to meet research needs across all disciplines. The ships enable oceanographic research in the most extreme and remote oceanic environments on Earth. Over fifteen years of NERC investment has created the largest and most diverse fleet of robotic research vehicles in Europe, including 10,000 items with a collective value estimated at £20 million. NERC unmanned vehicles go further and deeper than any commercial or military capability.

The Facility for Airborne Atmospheric Measurements (FAAM) is Europe's largest flying atmospheric laboratory, housed in a modified BAe 146-301 aircraft. The aircraft carries a large and versatile suite of instrumentation to characterise processes throughout the troposphere up to around 10km altitude. Barring Antarctica, it is capable of operating anywhere in the world. The FAAM provides the UK atmospheric science community with a world-class platform for airborne research, to support research in areas like weather, climate, air quality and Earth observation.

National Oceanography Centre



National Centre for Atmostphere Science

UKRI

The infrastructures within the environment sector are broad, diverse and geographically distributed across the country. Seventy-eight per cent of environmental infrastructures are located outside of London and south-east England. Nearly two thirds (66%) are single site focused, with a quarter distributed or grouped. A small number (7%) identify as a hybrid/mixed model, for example, the Svalbard Integrated Arctic Earth Observing System which has physical and virtual assets.

The environmental science research sector has many strengths in different places and organisations including HEIs, government departments and agencies, PSREs such as the Met Office and UK Research and Innovation and its NERC research institutes. Non-governmental organisations have a small yet influential research portfolio. Regarding the legal structure, the vast majority (88%) of environmental infrastructures are located within a legal entity, such as a university or research institute. The remaining infrastructures are evenly split across short-term externally funded projects, national and international legal entities.

Environmental infrastructures are in high demand with just over half reporting an increase in demand over the last ten years, with an expected increase in demand in physical, virtual and remote access as shown in Figure 12.2.

Environmental infrastructures are often of national and international importance and uniqueness. Thirty per cent of users at UK-based infrastructures have come from outside the UK. Over half (56%) of infrastructures stated their users would have to travel outside of the country to access a similar capability. Most importantly, a quarter (26%) identified that there was no other similar capability in the world; these included Birmingham's Institute of Forest Research Free Air Carbon Enrichment Facility (Figure 12.3).

The global challenges we are facing 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 overwhelming majority (96%) of environmental infrastructures collaborate with other infrastructures and organisations and 86% collaborate internationally (Figure 12.4). This wide collaborative scope is further demonstrated by 95% of infrastructures attracting users from other countries.

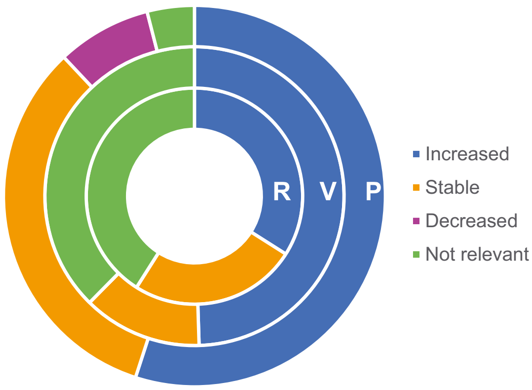


Figure 12.2. Expected change in demand for environmental infrastructures for Physical (outer ring – P), Virtual (middle ring – V) and Remote access (inner ring – R) over the next 5-10 years.

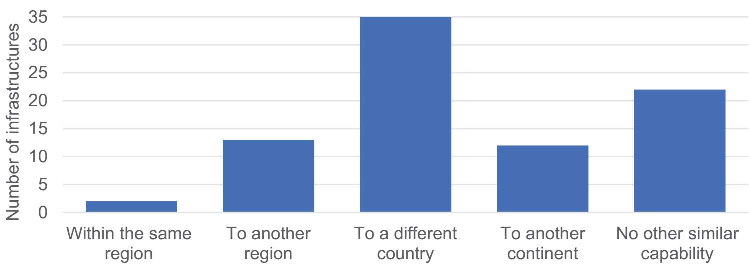


Figure 12.3. Distance that users of environmental infrastructures would have to travel to access a similar capability.

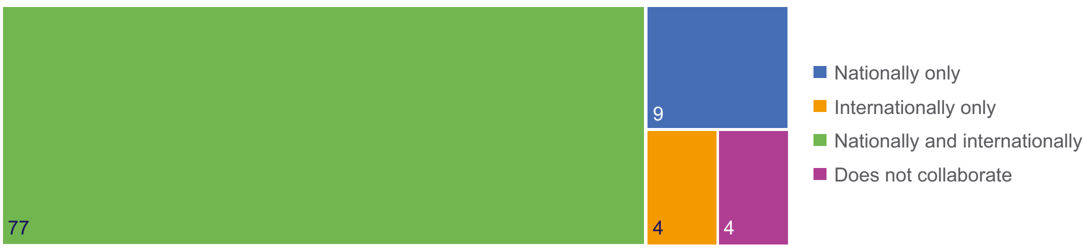


Figure 12.4. Number of environmental infrastructures that collaborate with other infrastructures and organisations nationally and internationally.

Case study:
Tackling the space weather threat

Geomagnetic storms are rapidly becoming one of the biggest potential threats to modern society. They can cause serious damage to power grids, communications satellites and other vital infrastructure. The potential ongoing costs from a single serious event have been estimated at up to £1.3 trillion a year.

EISCAT_3D, the next-generation European incoherent scatter radar system, is an international collaboration that will deliver more sophisticated radar observations to improve our understanding of the Earth's atmosphere and its interaction with the geospace environment, including space weather monitoring and forecasting. UK environmental science has contributed £6.2 million of the €65 million cost to build EISCAT_3D.

C. Heinselman

Courtesy of The National Institute of Polar Research, Japan

This high level of attraction on the international stage is due to infrastructures offering a better overall package, e.g. support (57%), a unique capability (51%), being part of an international collaboration (54%) or being higher-quality (41%). Furthermore, over a quarter (27%) expect that the number of international users is likely to increase.

The environment sector had the highest number of infrastructures (70%) with an expected operational lifespan of over twenty-five years, compared to the average of 60%. Continuity of long-term infrastructures for sustained observations and the collection of long-term data sets is vital for the sector, such as the Met Office Observations Network that has been in operation since 1853. The clear majority of environmental infrastructures (92%) are in operation, with the remainder in development (2%), design (3%) and implementation (3%).

12.2 Impact and outcomes for the economy, industry and policymaking

Environmental science stimulates clean growth, avoids costs to allow industry to remain resilient to risk and shocks and supports effective policy-making. Environmental infrastructures are associated with economic activity such as public policy, agriculture, mining and health services (Figure 12.5). Additionally, 71% of environmental infrastructures work directly with UK businesses and 59% directly contribute to shaping public policy and delivering public services. Over half (57%) provide resources and/or related services to the wider community in addition to providing the infrastructure itself.

Case study:
Creating new insights by unlocking our geological past

The National Geological Repository (NGR) includes the largest collection of UK geoscience samples, with 16 million specimens curated over the past two centuries. It includes over 23,000 rock cores from boreholes and hydrocarbon wells around the UK, the major British collection of rocks and over 3 million micro- and macrofossils – all available for inspection. The NGR collections are being scanned and digitised and made available online, including over 1.3 million scanned UK onshore borehole records. The NGR has been used, for example, by energy firms to avoid unnecessary drilling costs of around £12 million per well and by mining companies looking for new sources of critical metals.

BOSCORF is the UK national repository for deep sea sediment cores providing specialist long-term storage and curation for over 2500 sediment cores. The collection is growing by 100-200 cores per year and includes cores from all major ocean basins. BOSCORF provides researchers with access to this essential marine collection and enables scientists to carry out high impact science.

National Oceanography Centre

British Geological Survey

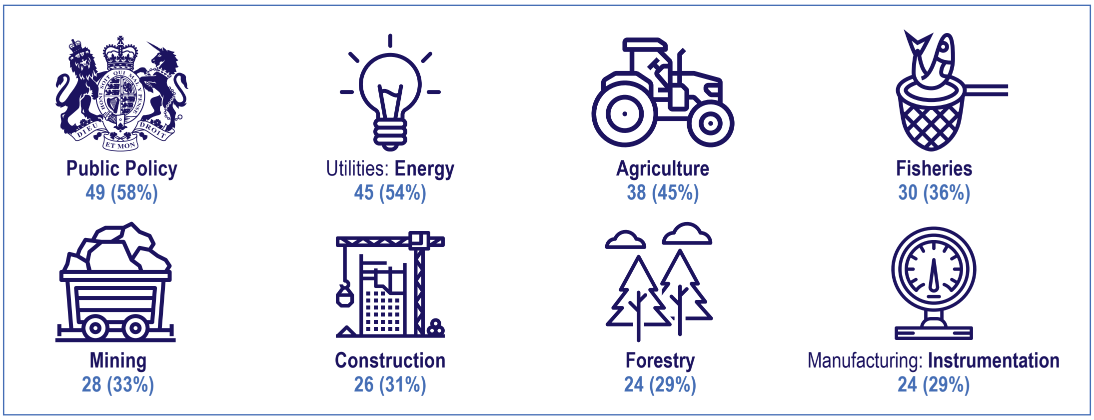


Figure 12.5. Top economic sectors that environmental infrastructures contribute to or work with (excluding research and education).

The environment sector uses innovative and world-leading infrastructure to respond rapidly to natural hazards and emergencies. Infrastructure provides our scientists, technicians and partners with the tools to predict, manage risk and ensure that, in the UK and globally, people and business can prosper in a resilient, productive and healthy environment. This is becoming increasingly important as environmental science infrastructure provides the data, insights and modelling to the UK and its partners to find environmental solutions such as the challenges presented by climate change.

A partnership between the University of Leicester and local businesses secured wider utilisation of space-based Earth observation (EO) data, enabling forty SMEs to increase their total GVA by £950,000 within four years. The partnership achieved this via targeted interventions, development of products and services and training in the use of EO data, generating £2.9 million of investment in the East Midlands economy.

For more than thirty years marine infrastructures have underpinned pioneering conservation biology research by environmental scientists, to support the UK government's leadership role in influencing international policy and delivering environmental benefits and income from sustainable fisheries. Bird Island and King Edward Point research stations and the RRS James Clark Ross are critical infrastructures in Antarctica and the sub-Antarctic. They have enabled critical expertise and evidence to be gathered for international policies and agreements to protect and conserve marine and terrestrial ecosystems, as well as to sustainably manage Southern Ocean fisheries. This has resulted in a large area of the Ross Sea region being designated a Marine Protected Area and the virtual elimination of seabird mortality associated with fishing.

The UK's environmental infrastructure also enables economic, societal and policy benefits across the globe, delivering against Intergovernmental Panel on Climate Change (IPCC) commitments and the Sustainable Development Goals. Infrastructure provides researchers with the tools to produce innovative solutions to challenges all over the world. For example, environmental scientists have used weather predictions to reduce poverty and secure farmer livelihoods in Africa. These forecasts have delivered significant benefits to governments, businesses, aid agencies and communities by improving national weather services, providing early warning of crop failure and enabling poor farmers to take out commercial insurance against weather shocks.

Case study: Responding rapidly to emergencies

Following the eruption of the Eyjafjallajökull volcano in Iceland in 2010, volcanic ash disrupted aviation on a global scale with huge economic losses. Met Office innovations in ash dispersion modelling and forecasting, underpinned by FAAM, avoided the unnecessary closure of UK airspace and saved airlines £290 million per day.

S Mobbs NCAS

G Gratton FAAM

Case study:
Early weather warnings save lives and reduce costs

NERC-funded researchers at the University of Reading worked with the Met Office to develop computer models that can identify 'sting jet' airstreams and predict severe winds several days in advance. This enabled the Met Office to strengthen its severe wind warning service and deliver annual savings including:

- Twenty-three lives: due to work being suspended on high buildings in extreme winds
- 350,000 tonnes of CO_2: by reducing fuel needed for aircraft diversions
- £120 million: by enabling airlines to improve aircraft routing
- £5 million: from emergency services making more informed resourcing decisions

National Oceanic and Atmospheric Administration

A model developed by NERC's National Centre for Atmospheric Science provides airports with warnings of severe winds. Now incorporated into Met Office forecasting models, it saves £1.25 million per year for the Ministry of Defence in the Falklands, for instance, by minimising flight diversions.

Tropical Applications of Meteorology using SATellite data (TAMSAT) and ground-based observations, for example, recently enabled US$2.8 million to be paid to farmers in 370 locations in Zambia following a severe dry spell. The farmers are part of a mandatory insurance scheme introduced by the Zambian government to protect farmers against extreme weather events, the largest scheme of its kind in Africa.

12.3 E-infrastructure and data needs of the sector

Tackling environmental challenges requires innovative ways of modelling, simulating and observing the environment. There is an increasing need to manage large, interoperable data sets, which come with challenges such as variable data quality. Of the UK's environmental infrastructures, 72% have a significant e-infrastructure and/or data requirement and two thirds are also associated with the computational and e-infrastructure sector. Over three quarters (76%) envisaged e-infrastructure and data becoming more relevant to them in the next five to ten years.

The environment sector has a world-leading data analysis and storage infrastructure known as JASMIN and globally competitive HPC capabilities through the UK's national supercomputer ARCHER. JASMIN is a globally unique data-intensive supercomputer for environmental science and currently supports over 160 science projects. Its users' research topics range from earthquake detection and oceanography to air pollution and climate science. JASMIN has more than 44 petabytes of available storage, equivalent to storing over 10 billion photos. The sector also benefits from NEXCS, MONSooN and its successor Monsoon2 to deliver supercomputing infrastructure to enable collaboration between NERC and the Met Office in climate and weather modelling. It provides a common computing platform, post-processing capability, a fast data link and access to data archives.

Chapter 13: Energy sector

andreas160578 from Pixabay

Energy research and innovation infrastructures cover a broad range of R&D, from underpinning science in universities through to large demonstration facilities. It encompasses a diverse range of research areas that can be categorised as follows:

Power generation

- Nuclear Fusion and Fission
- Renewable generation (wind, marine, wave, tidal, solar and geothermal)
- Fossil Fuels (oil, gas and coal)

Energy distribution

- Electrical power network systems
- Natural gas distribution networks
- Alternative energy vectors (hydrogen and fuel cells, alternative fuels including biofuels)

Enabling technologies

- Energy Storage
- Carbon capture and storage
- Energy efficiency and demand reduction (buildings, transport and industry)
- Whole energy systems understanding. Including energy demand, policy and regulation

Energy research also includes supporting technologies such as electrochemistry, materials science, systems engineering, robotics, remote and autonomous systems and advanced manufacturing. Much of the underpinning science for energy research is undertaken in facilities that are cross-cutting in nature and which have not identified energy as their primary sector. Examples include the Sir Henry Royce Institute, Diamond, National Physical Laboratory infrastructures in the PS&E sector and the British Geological Survey facilities in the environment sector.

Energy R&D is a strategic priority for the UK and is a key component of the government's Industrial Strategy[1] and Clean Growth Strategy[38]. The key high-level challenges for energy R&D in the UK include:

- Development of low carbon, secure and affordable energy technologies
- Transition from the current fossil fuel based energy system to a future low carbon system
- ntegration of intermittent renewable energy sources into the energy system
- Decarbonising sub-sectors of energy including heat, transport and industry
- Development of energy storage in all the energy vectors including electricity, gas, heating and cooling

13.1 Current landscape

Given the focused subject area, the energy sector consists of a relatively small group of dedicated infrastructures. Thirty-three infrastructures identified energy as their primary sector in the questionnaire responses. However, as noted above, a significant number of infrastructures within other sectors provide crucial underpinning research capability. Forty-four percent of the 718 non-energy infrastructures also cover energy as a part of their remit and support underpinning science for energy R&D. This indicates that there is a strong link between energy and the other sectors (Figure 13.1), especially the PS&E, computational and e-infrastructure and environment sectors.

Power generation

The FloWave Ocean Energy Research Facility is a marine energy research facility constructed for cutting-edge academic research into wave and tidal current interactions. FloWave is also a cutting edge tool for commercial developers to ensure their technologies and projects perform 'right first time' and are de-risked as much as practical before cutting steel or going offshore.

UKRI and Mr Stuart Brown

Energy distribution

The University of Manchester High Voltage Laboratory (officially called the National Grid Power Systems Research Centre) is the home to research funded by industry, the UK government and the EU. The mixture of highly skilled researchers and academics provide the edge in innovative and experimentation consultancy that is not found in other services. The lab, along with its test facilities, is capable of working with existing utilities and development companies in testing and assessing equipment at high voltages. The staff are capable of providing consultancy for the needs of today's transmission and distribution expansion and innovation.

Enabling technologies

The recently founded Faraday Institution is the UK's independent institute for electrochemical energy storage science and technology, supporting research, training and analysis.
The Faraday Institution brings together scientists and industry partners on research projects to reduce battery cost, weight and volume to improve performance and reliability and to develop whole-life strategies from mining to recycling to second use.

Energy infrastructures are distributed in all four countries of the UK, with particular concentrations in south Wales, Scotland and central England. Of the infrastructures identifying energy as their primary sector, 91% also identified with PS&E and 64% were also relevant to the environment sector. For example, energy is the primary sector of the Edinburgh Centre for Carbon Innovation (ECCI) and the East Riding of Yorkshire Council (Ergo), but they also identify strongly with environment as well. The Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings (SPECIFIC) and National Nuclear Laboratory (NNL) both mentioned that energy is their primary sector, whilst they also cover PS&E.

The majority of energy infrastructures (82%) are single site physical entities, which again is a higher percentage than the other five sectors. Many of the smaller, more highly focused facilities tend to be located in universities, such as the FloWave Ocean Energy Test Facility at Edinburgh University. Co-locating in a university provides the supporting scientific capability in areas such as materials research that underpin this sector.

13.2 Recent investments

Many of the infrastructures in the energy sector are relatively new with 81% of the identified infrastructures having started operations within the last fifteen years. This is due to the increased investment in energy R&D that has taken place over the period, investment that has been made in response to internationally recognised future clean energy[39] needs. For example, spend on the EPSRC-led UK Research and Innovation energy programme has increased from around £30 million per annum to around £180 million per annum since 2004. The Energy Technology Institute (ETI) was created in 2008 with a ten-year budget of up to £100 million per annum that was 50:50 public/private funded. At the same time there has been a significant expansion in energy R&D support by BEIS. Recently the UK government has pledged to double energy R&D to around £400 million per annum as described in the Mission Innovation programme[40].

Recent investments reflect the relative economic and political importance of different energy technologies. For example, the expansion of generating capacity for offshore wind energy between 2008 and 2018 from under 0.5GW to over 8GW of installed capacity has been supported by significant infrastructure investment in ORE both prior to and during the expansion. Facilities such as the ORE Catapult, the Flowave and COAST facilities all contributed to building understanding of and overcoming the engineering challenges associated with placing generation infrastructure in the sea.

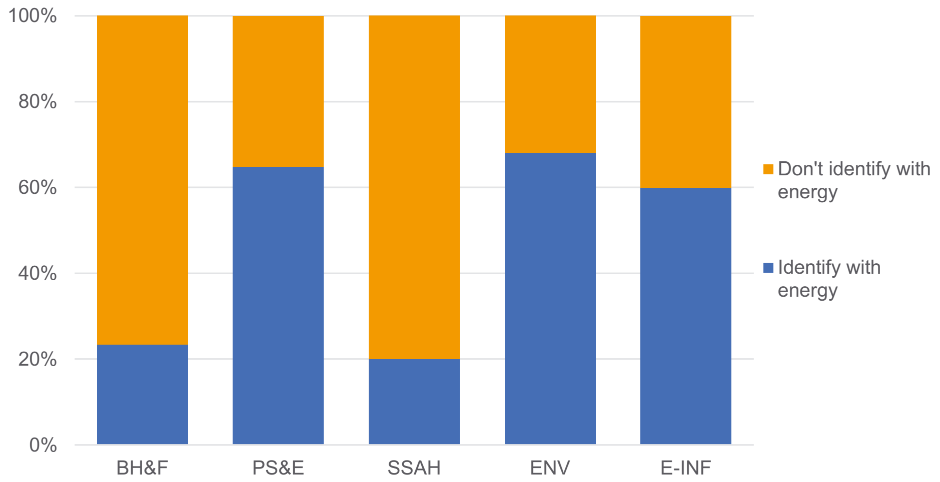


Figure 13.1. Distribution of infrastructures from the other five sectors that identified with energy. Identification was particularly strong in the physical sciences and engineering, environment and computational and e-infrastructure sectors.

Case study:
Coastal, Ocean And Sediment Transport (COAST)

Housed in the Marine Building at the University of Plymouth, the COAST laboratory provides a range of world-class physical modelling facilities. Physical models are powerful tools that facilitate the understanding of the potential behaviour and de-risking of engineering projects.

COAST

Waves, currents and wind are generated at scales suitable for research, design and optimisation studies across the ocean, coastal and fluvial engineering and physical science sectors. Recognised as an international centre of excellence for research, development and teaching in these fields, COAST's clients include central and local UK Government, the European Commission and international funding agencies, as well as consultants, contractors and developers. Since its inception in 2012, COAST has become a leading light in the global drive to further the learning and development of the nascent marine renewable energy sector, and is seated at the heart of the collaborative Supergen ORE Hub.

More recently there has been significant investment in nuclear fission R&D facilities, mostly in universities or building on existing capability in NNL, Sellafield Ltd, the Dalton Cumbria Facility and UK Atomic Energy Authority (UKAEA) at Culham. This investment is ongoing and includes recently approved additional support for the National Nuclear User Facility (NNUF) phase 2 expansion. This expansion in infrastructure is in recognition that the UK needs to develop and commission the next generations of nuclear technologies. In scale and diversity nuclear facilities reflect general energy infrastructure, with some being distributed, such as NNUF and some being single site national capability, such as NNL. Facilities exist as single-sited either because they deal with highly specific challenges, such highly active materials at NNL, or because they serve a specific market that is sufficiently large to warrant a single energy research area. Where demand and expertise are distributed, distributed infrastructures can be more appropriate to avoid having to relocate and centralise capability, or to avoid the duplication of capability, e.g. NNUF.

Not all of the energy research infrastructure is focused on middle or high Technology Readiness Levels (TRLs)[41] . For example, the UK has a strong track record in nuclear fusion research and the UKAEA facility at Culham Centre for Fusion Energy (CCFE) has hosted the Joint European Torus (JET) and Mega Amp Spherical Tokamak (MAST) facilities since the early 1980s. The work undertaken at CCFE involves a breadth of research including cutting-edge plasma physics and plasma control and the development of new materials, robotics and control systems that can withstand a highly hostile operating environment. It should be noted that the fusion facilities are a good example of international facility collaboration and play a unique role in contributing to the UK's international obligations (e.g. JET). They can also form a nucleus of expertise around which a national programme can coalesce, e.g. MAST.

In other energy areas the UK has more modest capabilities, with most of the facilities being located in universities:

- **Solar energy:** the UK has a scientific lead in many cutting-edge solar energy technologies (thin film photovoltaic (PV), organic/dye sensitised PV and perovskite PV). The SPECIFIC Innovation and Knowledge Centre, a facility in Port Talbot and the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University are the two significant centres in solar energy

- **Bioenergy:** outside universities there is little infrastructure in bioenergy. The UK does have facilities in agriculture, plant breeding and genomics, captured in the environment sector, but little on the conversion technologies to turn biomass into fuels
- **Power distribution:** infrastructure is mostly focused on electrical distribution facilities at Strathclyde and Manchester universities
- **Hydrogen and Fuel cells:** research is mostly undertaken in universities
- **Energy system transition:** the UK's capabilities are modest

The UK energy system is undergoing a slow but fundamental transition as increasing low-carbon energy sources are brought online. It is unclear exactly what the future energy landscape will look like or what mix of energy sources will predominate, but it is clear that the future system will be smarter and more connected and have to co-ordinate a wide variety of energy sources. As a consequence, there is a growing infrastructure capability in smart metering/systems and the associated data, modelling and simulation that is needed to understand the impact of these changes and to develop the technology required to enable them. Much of this capability is in UK universities, who are the developers and custodians of most of the energy system models, but there are increasing links between the academic capability and industry, facilitated by institutions such as the Energy Systems Catapult.

13.3 The role of data & e-infrastructure in the sector

Two thirds of energy infrastructures report a 'significant e-infrastructure/data requirement or component'. E-infrastructure is seen as necessary by the sector to address the challenges of capturing data, undertaking complex modelling and the simulation of various subsectors/subsystems with the aim of ultimately being able to simulate the entire energy system. E-infrastructure is also needed for applied solutions to real sector issues, such as the real-time monitoring of remote facilities (e.g. wind farms) which is valuable for performance checks, early detection of faults and errors and ensuring the security of the system is intact. Three quarters of energy infrastructures consider that e-infrastructure and data will become more relevant over the next five to ten years.

In the energy sector data are a particularly valuable resource that can be used to inform models, improve accuracy of forecasting and cost optimisation, inform policy interventions and help businesses to develop. These data can come in many forms, such as individual user data, weather data for prediction of peaks and troughs in electricity production, systems performance and control data needed for maintaining grid stability and market data for ensuring optimum efficiency for suppliers and consumers. It is important that researchers, businesses and aggregators have sufficient access to data to enable informed decisions. Hence data are a valuable asset and are legally protected both as company property and the property of the individual customer.

In future energy systems, the integration of varied and new sources and types of data may pose challenges in terms of both storage and coordinated security policy, which may be solved by investing in the link between the computational and e-infrastructure and energy sectors. Future energy infrastructures need to be linked digitally together to enable the exchange of data, models and results – otherwise whole or even partial energy systems cannot be modelled or controlled. E-infrastructure can also enable digital twinning technology development for the energy sector using a sensor-enabled digital replica of the energy system. This may enhance the potential for multi-vector and multi-sector energy infrastructure applications by developing joint energy-computational and e-infrastructure infrastructures.

13.4 Energy as a key economic sector

Energy is a key economic sector and as such is highly regulated. Almost no energy generation technologies can be installed without either certification of the technology (e.g. nuclear) and/or permissions for installation (e.g. offshore renewables). This means energy technologies need to be thoroughly understood before they are allowed to market, resulting in a strong driver for technology development, testing and certification capability. Hence, energy is the only sector where every infrastructure has significant involvement with business across the board and it has the highest skew in output towards commercialisation (Figure 13.2).

Energy infrastructures are mainly seen as important by the utility companies and the energy supply chain (Figure 13.3). Other economy sectors that energy infrastructures have a strong relevance to include public policy, transportation (automotive, aeronautical), manufacturing, instrumentation and construction. This emphasises that energy infrastructures make a wide breadth of economic contributions and play a pivotal role in the reduction of carbon emissions across the UK economy almost regardless of sector.

While most R&D-focused infrastructures have been constructed and operated using public funding, the majority of development – and deployment-focused infrastructures are both public- and industry-funded. They represent a shared or pooled resource that is available to multiple industries and academia and that draws on UK academic expertise. Where infrastructures are cost- and use-effective for industry to build themselves they do so, such as the Integrated Transport Electricity and Gas Research Laboratory InTEGRel[42], which is led by Northern Gas Networks and is in partnership with Northern Powergrid and Newcastle University. This public-private funding model is particularly evident where there are more nascent markets, which require government support for pre-commercial activity to prove and de-risk new technology. This dual-support model is highly desirable as industry is faced with applied problems that the academic research base is well placed to help solve, while academia gains access to unique challenges that can push the frontiers of science.

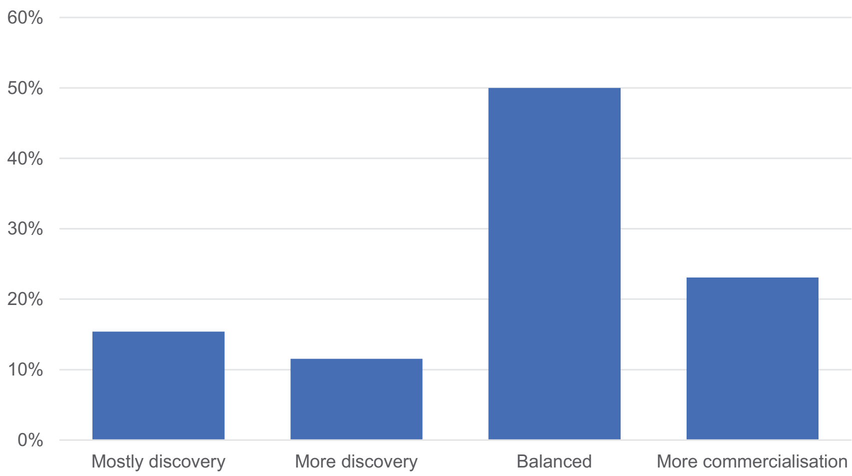


Figure 13.2. Distribution of energy infrastructures on a discovery-to-commercialisation spectrum.

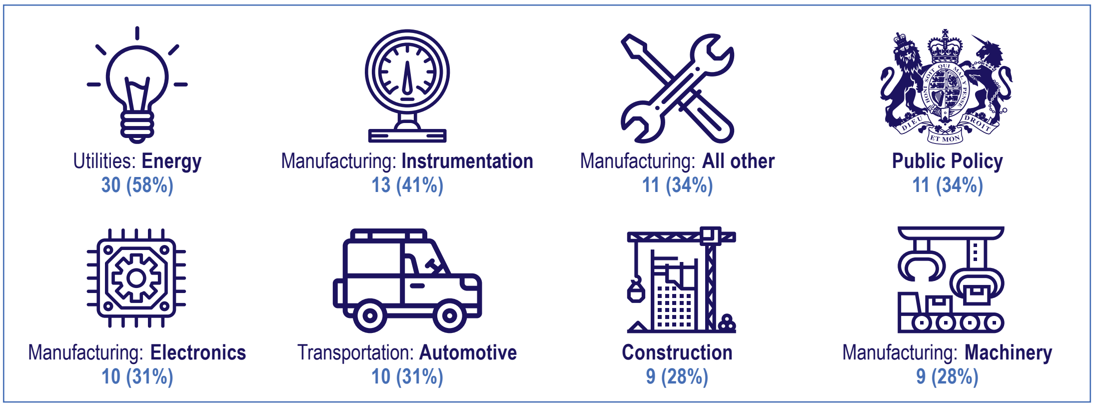
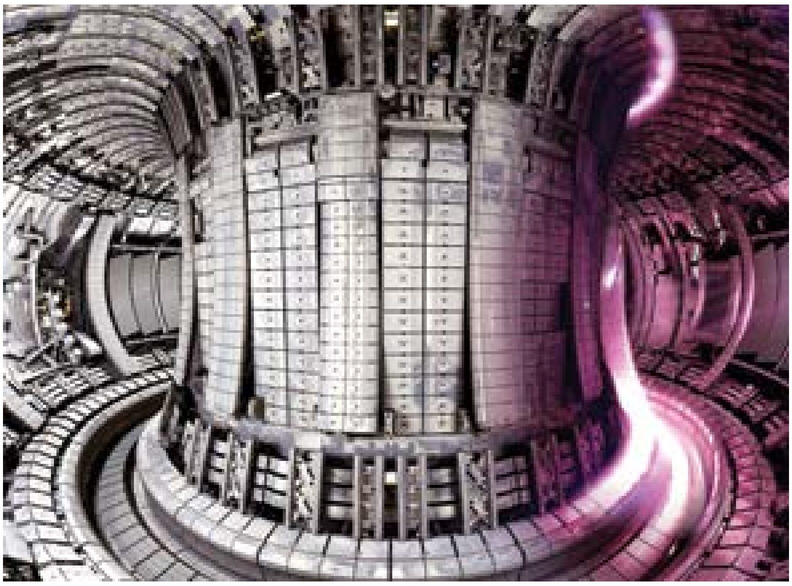


Figure 13.3. Top eight sectors of the economy that energy infrastructures work with or contribute to (excluding research and education).

Case study:
Fusion energy infrastructures at UKAEA



EUROfusion

UKAEA's campus at Culham in Oxfordshire is one of the world's leading collections of fusion energy research infrastructures. Its main mission is to lead the commercial development of fusion power and related technology and position the UK as a leader in sustainable nuclear energy. UKAEA at Culham houses a number of energy infrastructures.

JET at Culham is the world's largest magnetic fusion experiment and is also the largest EU facility in the UK. It explores the potential of fusion as a source of energy using a tokamak, an infrastructure that holds hot plasma in a tight magnetic field. As atoms fuse, energy is released and absorbed as heat in the walls of the vessel.

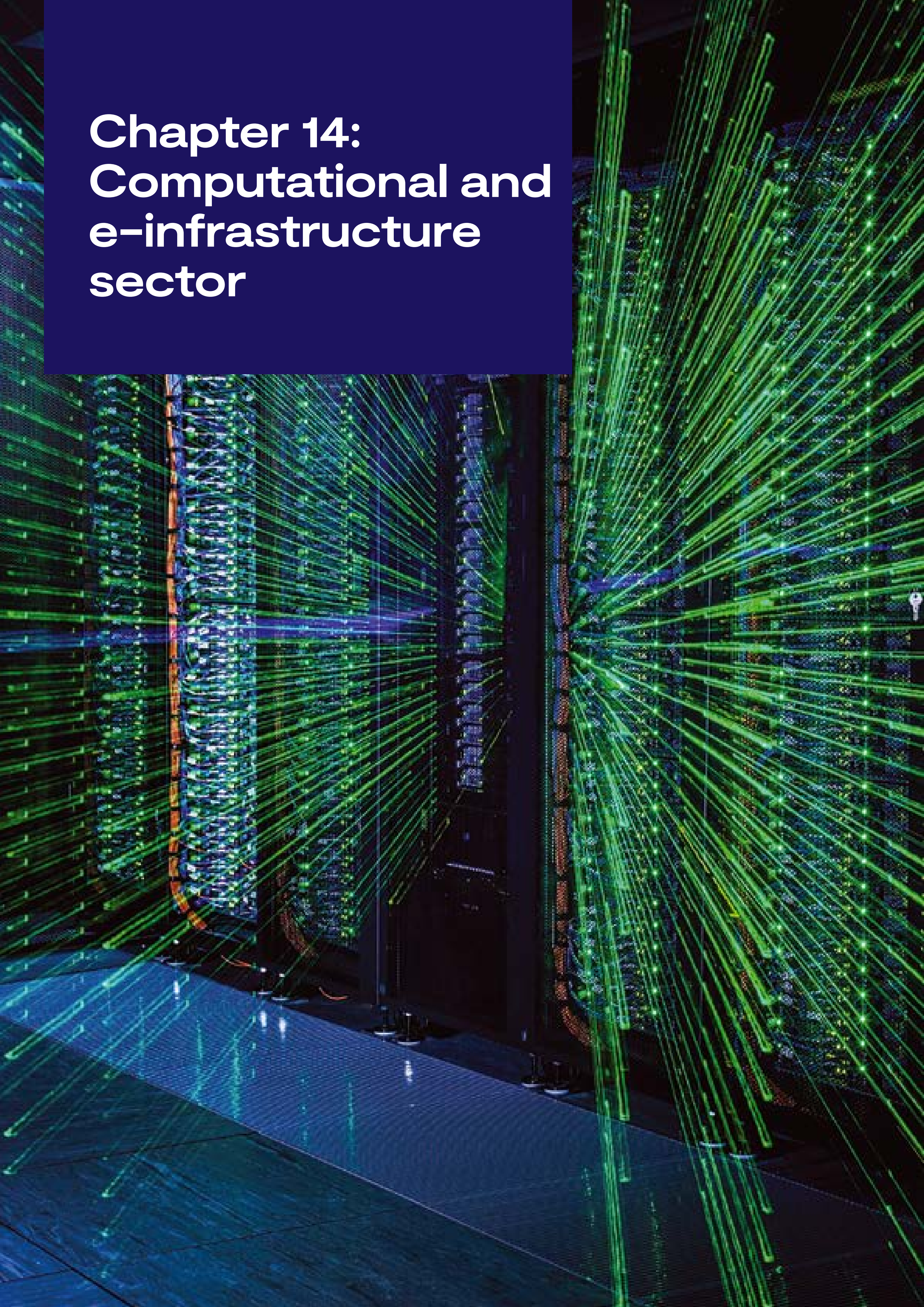
MAST is the UK's fusion energy experiment. MAST holds plasma in a tighter magnetic field than conventional tokamaks like JET by forming a sphere shaped plasma rather than a doughnut. This has the potential to produce more economical and efficient fusion power.

UKAEA

The Materials Research Facility (MRF) has been established to analyse material properties in support of both fission and fusion research. It is part of the NNUF initiative, launched by the government and funded by EPSRC, to set up a multi-site facility giving academia and industry access to internationally leading experimental equipment. The MRF is also part of the Sir Henry Royce Institute for Advanced Materials.

Monty Rakusen

Chapter 14: Computational and e-infrastructure sector



The term e-infrastructure covers all infrastructure that enables digital/computational research. It should be regarded as 'scientific instrumentation'. The building blocks are shown in Table 8.1.

Table 8.1. The building blocks of e-infrastructure

Networks	International/national (GÉANT and Janet), local
Software	Tools (operating systems, digital and software libraries, access management systems etc.) Application codes (modelling, simulation, data analytics)
Computers	Supercomputers High-throughput computers for data analysis
Data infrastructure	Infrastructure for moving, storing, analysing, visualising and archiving data
Access mechanisms	Cloud technologies Access management and identity management technologies

Computation and e-infrastructure is an important underpinning component of the research ecosystem across UK Research and Innovation and is critical to the operations of a number of public sector bodies such as the Met Office. Jisc is the UK's provider of digital solutions to research and education. This includes the superfast Janet network, Eduroam, domain registries, digital content, training and infrastructure.

The current UK e-infrastructure ecosystem has evolved over many years rather than being 'designed'. This reflects the diversity of the communities supported and the range of funding sources and mechanisms. Over the last five years a strong culture of collaboration has been developed amongst key e-infrastructures across all fields. The UK is in a good position to build on these foundations and explore the scope for increased collaboration and sharing of e-infrastructure in the future, including linking into global initiatives such as the European Open Science Cloud (EOSC) and EuroHPC.

Seventy-two percent of infrastructures from other sectors reported a requirement for e-infrastructure. It is likely that this underrepresents the actual requirement because computational and digital approaches are becoming ubiquitous across all fields of research.

14.1 Current landscape

The computational and e-infrastructure sector has strength in diversity, reflecting the diversity of research needs. This degree of diversity defies easy categorisation, but Figure 14.1 attempts to capture it.

At the centre of computational and e-infrastructure landscape are the people: both the academic and industrial users, and the experts who run the services. The infrastructure is dependent on the Janet network to provide access routes and the technology for moving data. A key element is the software infrastructure. A significant majority of research across all disciplines relies on specialist research software for modelling, simulation and analysis. Software is where much intellectual property, knowledge and understanding resides and this is why software has such longevity. People replace their compute and data hardware, but do not dispose of their codes. Software should be considered a research output in its own right and forms key infrastructure. Finally, there are the diverse hardware components, such as computing and data platforms, tailored to meet the research and innovation requirements of users.

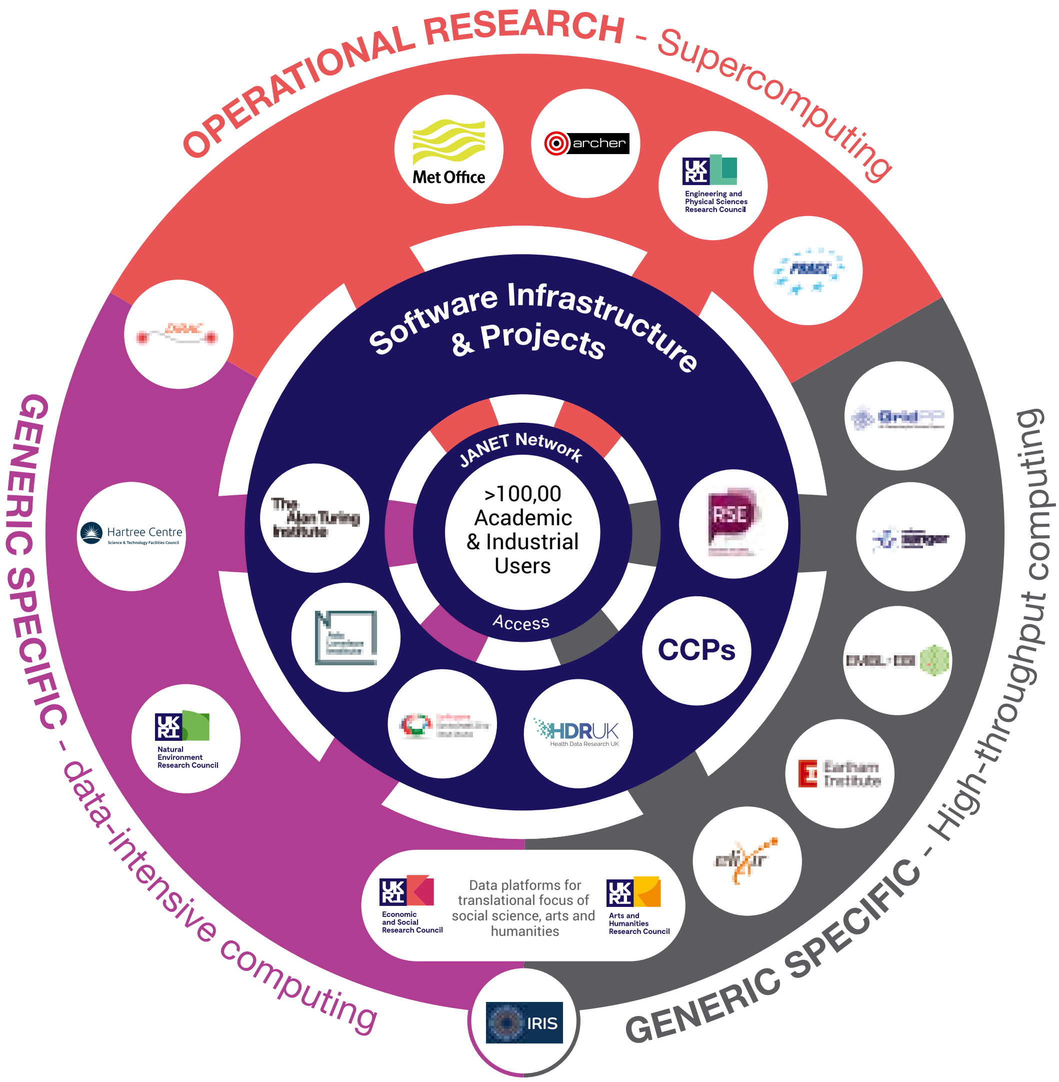


Figure 14.1. The UK's current national research and innovation e-infrastructure ecosystem.

The use of e-infrastructure is significant across all sectors (Figure 14.2). It is used as a tool in 59% of infrastructures that did not identify e-infrastructure as their primary sector. It is the primary discipline of 17% of BH&F infrastructures and around 10% of PS&E, SSAH and environment infrastructures.

Case study:
UK Data Service (UKDS) and retirement income

The UKDS is an ESRC-funded infrastructure partnership between between Essex, Manchester, Edinburgh and Southampton universities, University College London (UCL) and Jisc. It provides training, support services and access to major UK government-sponsored surveys, cross-national surveys, longitudinal studies, UK census data, international macro-data, and business and qualitative data.

Research by the Resolution Foundation used a combination of data resources from the UKDS and Office for National Statistics (ONS) to assess future pensioner income. For their analysis of outcomes for recent cohorts of pensioners, the foundation used data from the British Household Panel Survey and Understanding Society, its successor. Forward-looking projections used two ONS surveys: the New Earnings Survey and the Annual Survey of Hours and Earnings.

The researchers found that future pensioners should experience similar levels of earnings replacement adequacy assuming retirement at state pension age, compared with recent retirees. The analysis shows that the policies being implemented are preventing deterioration in outcomes across future cohorts of pensioners, but that ambitions for earnings replacement adequacy appear to remain quite far out of reach.

The results informed the discussion within the Department for Work and Pensions (DWP) policy paper Automatic Enrolment Review 2017: Maintaining the Momentum. DWP will lower the age at which employees are required to be auto-enrolled in workplace pensions from twenty-two to eighteen, as well as widening eligibility to workers in the UK who earn less than £5876 per year.

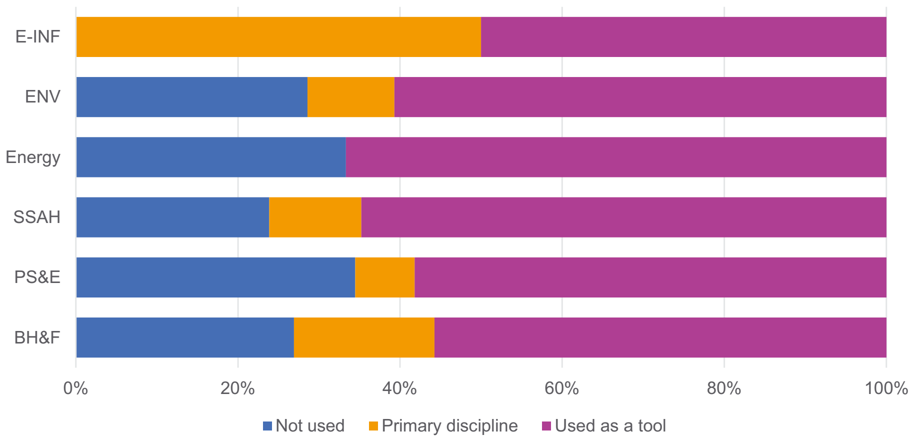


Figure 14.2. E-infrastructure usage by infrastructures in sectors that did not identify computational and e-infrastructure as their primary sector.

To understand the diversity, complexity and types of e-infrastructures we conducted a secondary classification of infrastructures, dividing them into the following:

- E-infrastructure facilities (e.g. ARCHER, Distributed Research using Advanced Computing - DiRAC)
- Experimental facilities with a major requirement for e-infrastructure to support the research that facility users are carrying out (e.g. Diamond, Square Kilometre Array)
- Data facilities and resources with a major requirement for e-infrastructure to support the research that facility users are carrying out (e.g. JASMIN, UKDS)
- Research centres/institutes that may have their own e-infrastructure to support research programmes, but which may require access to the three classes of e-infrastructure above (e.g. Earlham Institute, Health Data Research UK)

The majority of infrastructures (66%) fall into the fourth of these categories, around a quarter (24%) fall into either the second or third category and the rest (10%) fall into the first category.

Unlike sectors dominated by large, physical infrastructures that are visited in person, many e-infrastructures are accessed remotely over networks and, from a user-access point of view, their physical location is less information. However, for some of the experimental facilities that have an e-infrastructure requirement, users would still be likely to attend in person.

The hardware underlying e-infrastructure changes rapidly, with major refreshes needed on a timescale of three to five years. This is evidenced by the recent capital investments made in this sector (Figure 14.3). This may help explain why a larger proportion than in other sectors are reliant on short-term funding (28% versus an average of 14%). However, many infrastructures in this sector do have a significant lifespan (Figure 14.4). It is likely that the e-infrastructure capability itself may have a long lifespan, but the technology that it relies on will need regular replacement. For instance, Diamond will have a decades-long lifespan but during that time will need to upgrade and replace its data storage, software and research computing for data analysis and its network capacity.

The Research Councils performed a detailed questionnaire of e-infrastructure facilities in 2017 and the report generated from it contains considerable information about hardware, software, services and people[43]. From that questionnaire it was apparent that HEIs remain the main provider of data and compute services to the national e-infrastructure ecosystem, with thirty-six HEIs providing national or regional services.

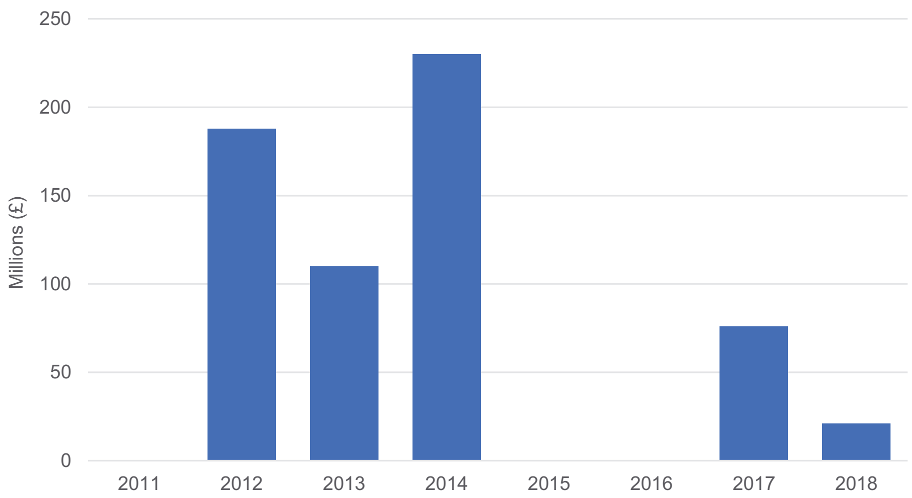


Figure 14.3. Recent capital investments made in e-infrastructure accessible to the wider academic community. Investments are largely aimed at maintenance of existing capability with the exception of funding of ARCHER2 in 2017.

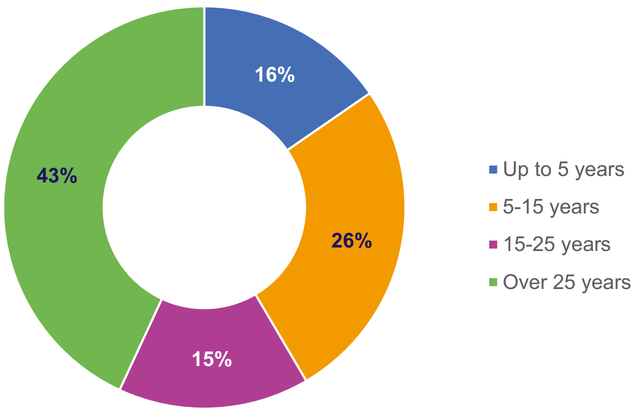
14.2 E-infrastructure, data and innovation

Data are often key to innovation. The Hartree Centre is an increasingly important infrastructure for UK industry and a centre of excellence in terms of how to apply HPC, cognitive computing and 'big data' expertise to a wide variety of industrial challenges. Continuing to develop this collaborative approach will boost the UK's competitive edge and help deliver economic growth and job creation.

Whilst Hartree is the only infrastructure directly targeted at industry, there is considerable industrial usage of other e-infrastructures via either academic/industrial collaborations or direct usage. Seventy-one percent of e-infrastructures stated that at least some of their work is informed by the needs of businesses. For example, ARCHER collaborated with Rolls-Royce to demonstrate the scaling of modelling across many applications. However, e-infrastructures generally support research at the discovery end of the spectrum (57%) or have a balanced portfolio (37%).

The top economic sectors that e-infrastructures contribute to in addition to research and education include communications, computing, health services, pharmaceutical manufacturing, public policy and transportation (Figure 14.5). What is not apparent from Figure 14.5 is the depth and diversity of economic sectors that are supported by e-infrastructures. Each e-infrastructure supports an average of seventeen economic sectors, far greater than any other domain sector and every sector of the economy is supported by at least a quarter of all e-infrastructures.

Figure 14.4. Expected operating lifespan of computational and e-infrastructures. Over half have an expected operating lifespan exceeding fifteen years.



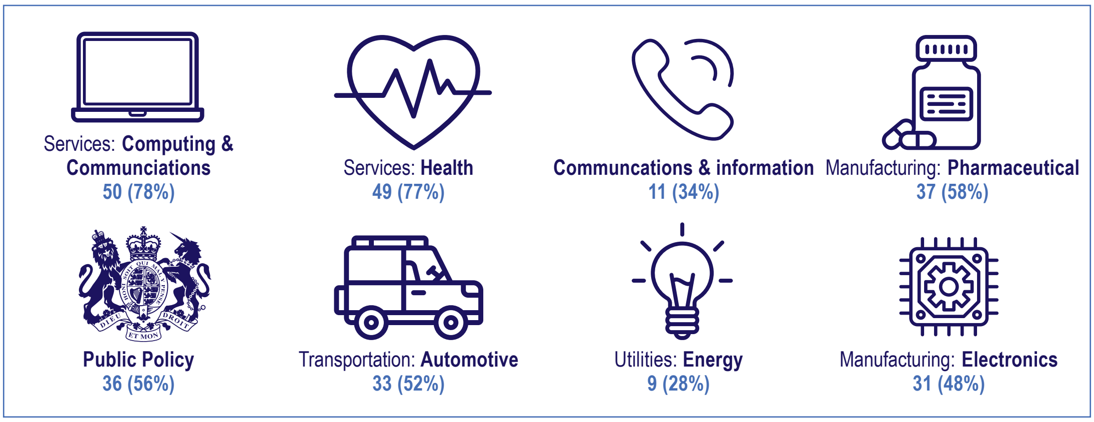
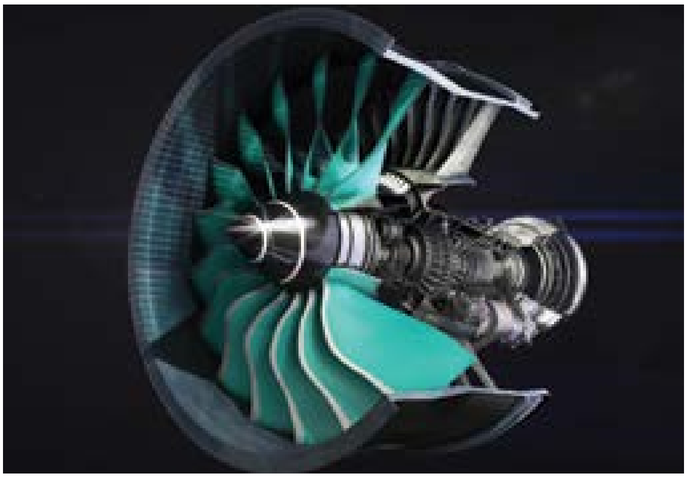


Figure 14.5. Top sectors of economy that computational and e-infrastructure infrastructures contribute to (excluding research and education).

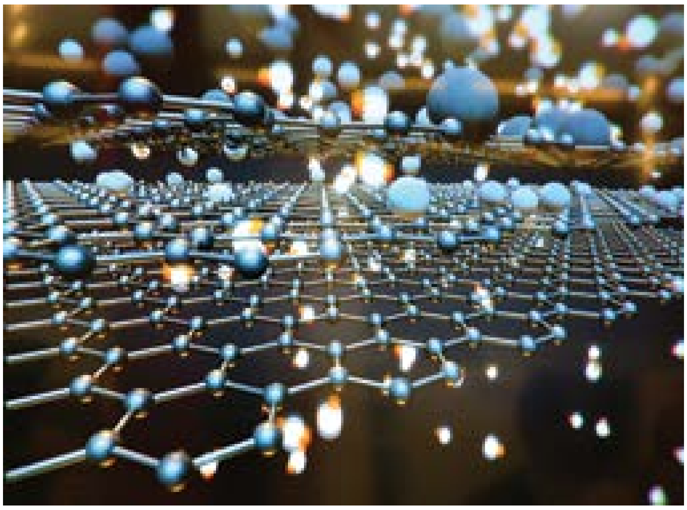
Case study:
Rolls-Royce and ARCHER


Rolls-Royce

Rolls-Royce use the national HPC service, ARCHER, to test the scaling of their codes for a variety of applications: fluid dynamics, noise, combustion and a structural model of a full engine test rig.

Rolls-Royce are major players in the aeronautical sector with an annual spend of £800 million and a total impact on UK Gross Domestic Product (GDP) of over £10.2 billion. Scaling is important to Rolls-Royce to ensure they can meet their design timescales and they were able to run a much larger scale on ARCHER. Access demonstrated the art of what was possible for Rolls-Royce and has set their computational science and engineering roadmap for the coming two to three years.

Case study:
The Materials and Molecular Modelling Hub



This hub provides researchers carrying out research into materials with access to a state-of-the-art HPC facility named Thomas after British physicist Thomas Young. Modelling and simulation enable fundamental insights into the processes and mechanisms that underlie physical phenomena and has become an indispensable element of contemporary materials research.

The facility was established in 2017. It is a partnership between EPSRC and a consortium of university partners: Imperial College, Kent, Kings College London, Oxford, Cambridge, Queen Mary, Queen's University Belfast, Southampton and UCL. As well as access to the supercomputer, the facility also offers training activities and skills development, plus community-building.

Annex A: Definition of research and innovation infrastructure used within this programme

Research and innovation infrastructures are diverse. The programme has drawn on the definitions used by ESFRI[44] and the Horizon 2020 Research Infrastructure Programme[11]:

> *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.*

Infrastructures can be single-sited (a single resource at a single location), distributed (a network of distributed resources), or virtual (the service is provided electronically) but are usually accessed through a single entry point.

This programme focuses on major research and innovation infrastructures supported through government and accessible to all users from academia and industry. In general this means:

- Evidence of sustained and/or substantial UK public funding commitment (to build, operate, upgrade, decommission) is required (can be through multiple channels)
- Private sector organisations and institutions funded by and for use of a single research establishment (e.g. a single university or PSRE) will be treated as out of scope
- Major research and innovation infrastructures within PSREs, UK universities or European and international organisations that are vital for the UK research and innovation community would be within scope

Requirement 1: purpose

An infrastructure must provide an essential platform to conduct or facilitate **excellent research and innovation that benefits the UK**, as demonstrated by independent assessment such as peer review. This could be through provision of equipment, facilities, analytical services, data and underpinning infrastructure. This might be encapsulated within a facility, research and innovation organisation or part of an organisation.

The infrastructure should be regarded and operated as a strategic capability enabling collaboration, supporting the meeting of specialist and technical needs and providing innovation in service support (e.g. regulatory compliance) which leads to efficiency of operation and reduced duplication (e.g. unique critical mass, coordination, scheduling).

in scope	out of scope
Access must be open to relevant, publicly-funded UK user communities beyond the owner/operator	Accessible to only one or a very limited number of researchers or organisations
Publicly-funded users may include HEIs, institutes, PSREs, research and technology organisations and other research and innovation organisations	Used only by privately-funded R&D (e.g. industry)
Access may extend to private or charitable users (e.g. industry), in addition to publicly-funded users	
Access may include international users of UK facilities and UK users of international facilities	
Access may be managed, e.g. through user registration, fees, competition, merit review, conditions, security; or it may be unmanaged	

Requirement 2: accessibility

An infrastructure must provide **access, resources or related services to the wider, UK research and innovation community** outside the infrastructure institution itself.

Requirement 3: scale and longevity

An infrastructure must **have some degree of strategic, international or national importance.** Some infrastructures which are currently regionally important but in key areas of emerging capability might also be captured.

An infrastructure should be:

- Assessed as critical for UK research and innovation excellence in one or more sectors (considered at frontier of knowledge, addressing the most pressing challenges, demonstrable UK leadership, cutting-edge quality, importance and relevance to one or more fields)
- Assessed as beneficial for UK research and innovation impact. This would include relevance and alignment with government economic and societal challenges and priorities. Evidence of importance to the user community through a range of pathways includes leverage of co-funding, role an infrastructure plays both within the local economy and at a national level

In addition there is an implicit expectation that short-term, focused projects without long-term sustainability (existing or planned and relative to asset and technology lifecycles) would not be within scope.

Annex B: Methodology

This final analysis of the UK's current research and innovation infrastructures has drawn heavily on data collected through two questionnaires that reached over 950 existing infrastructures. This annex first covers the content of the questionnaires, the approach taken to reach target respondents and response rates. It includes the approach taken to assess and fill any gaps in the data set and implement a classifications framework to support the more robust analysis presented here in the final report. This is followed by a section covering caveats on the data collected plus how best use of a valuable though imperfect data set has been made.

Throughout the initial analysis additional information gathered through workshops and stakeholder interviews, plus reviews of existing reports, has been used to sense-check messages from the data analysis and to provide supplementary insight on the infrastructure landscape. This annex does not go into detail on this supporting work.

Questionnaire approach

Questionnaires one and two were conducted during spring/summer 2018. The gap-filling questionnaire was conducted during winter 2018 and was an amalgamation of questionnaires one and two.

Broadly, the first questionnaire asked questions to gather a wide range of descriptive information on infrastructures. The second questionnaire sought to dig deeper in a small number of key areas and gather the views of infrastructures on future trends, as well as current/future barriers to maximising quality outputs. The following table lists the topics covered by the questionnaires.

Questionnaire one	Questionnaire two
Background information: ■ Description of the infrastructure ■ Location ■ Configuration (single site/distributed/virtual) ■ Strategic plans	**Legal nature:** ■ Legal nature of those infrastructures established as national legal entities
Lifecycle stage: ■ Stage of infrastructure in lifecycle ■ First year of operations ■ Lifespan	**Domain/sector:** ■ Relevance of Roadmap sectors ■ Relevance of subdisciplines within Roadmap sectors ■ Relevance of e-infrastructure (discipline of infrastructure versus used as tool) ■ Expected growth of relevance of e-infrastructure
Domain/sector: ■ Roadmap sectors covered ■ Primary sector ■ Significance of e-infrastructure ■ Sectors of economy supported	**Work with others outside academia:** ■ Contribution to public policy making/delivery of public services ■ Work with businesses, charities and the non-academic public sector at home and abroad
Scope & collaboration: ■ Scope/reach of infrastructure ■ Extent of access to external users ■ Provision of resources/services to wider community ■ Collaboration with organisations, nationally and internationally ■ Top collaborators ■ Extent of discovery versus commercial focused research ■ Extent of work with business	**Position in landscape:** ■ Access to UK users ■ Ease of substitution to alternative infrastructures ■ Complementary infrastructures in the UK and abroad ■ Attraction of users based outside of the UK
Users: ■ How user numbers are measured ■ Number of users ■ Where users are from	**Costs and decision points:** ■ Major decision points in the next five years ■ Direct and indirect funding from industry, charity and other non-government organisations ■ Potential for leveraging non-government contributions ■ Views of whether sources of funding will change
Capacity: ■ How capacity is measured ■ Percentage of capacity used ■ Target capacity use	**Reviews and evaluations:** ■ Whether infrastructure peer reviews users ■ Independent reviews of infrastructures
Costs: ■ Establishment costs ■ Annual costs of operations ■ Primary UK public funding source ■ Dependence on public finance ■ Whether infrastructure the result of a public-private partnership **Staffing:** ■ Headcount ■ Staff from UK and abroad ■ Female staff percentage ■ Black, Asian and minority ethnic staff percentage ■ Number of students	**Future trends:** ■ Technological drivers/trends impacting infrastructure in medium term ■ Scientific/research drivers/trends impacting infrastructure in medium term ■ Societal drivers/trends impacting infrastructure in medium term ■ Possible evolution of infrastructures to account for drivers/trends ■ Barriers to maximising quality outputs now and in medium term ■ Number of future years capacity/capability needs considered for ■ Trend in demand over last ten years ■ Expected growth of international users relative to national users

Target respondents and response rates

The target audience for the first questionnaire was all UK infrastructures and UK Research and Innovation undertook extensive preparatory work to identify as many as possible and to establish contacts. A list of almost 700 infrastructures with contacts was developed in consultation with sector experts, government departments, the cross-government analyst network and the Devolved Administrations.

These infrastructures were each invited to complete the first questionnaire. In parallel the questionnaire was promoted to all HEI vice chancellors by Research England and their devolved equivalents for wider coverage and to reach infrastructures with unknown contacts, plus hitherto unknown infrastructures. A link was also placed on the UK Research and Innovation website and promoted by the national academies, the Association of Innovation, Research and Technology Organisations (AIRTO) and others.

The first questionnaire was completed by 835 entities – 325 (47%) of the 697 infrastructures directly invited to participate completed the questionnaire, whilst 510 responses came about from the wider promotional work. Of the 835 responses, 712 fulfilled the criteria of being a national or international infrastructure and forty-three responses represented regional infrastructures. The second questionnaire was sent to everyone who completed the first questionnaire. The response rate for the 712 national/international infrastructures from the first questionnaire was 83%.

Data from the first and second questionnaire were used for the 'Initial Analysis report[7]', published in November 2018. One of the reasons for the Initial Analysis report was to stimulate further engagement with the community and to fill the gaps in completion with some sectors; for this purpose a gap-filing questionnaire was conducted in Winter 2018. As well as engaging new infrastructures, institutions which had completed the first and second questionnaires were identified and invited to complete the gap-filling questionnaire for their infrastructures. This ensured that we included data at the appropriate level according to the classification developed and presented in the Initial Analysis report and did not exclude responses that were otherwise important to the programme. The gap-filling questionnaire received a further 110 responses leading to a data set covering 945 infrastructures.

Classification framework

All questionnaire responses were independently classified according to two measures: organisational level (e.g. institution, sub-node) and uniqueness of capability. Questionnaire data, independent desk studies and verification from sector experts were used to inform and validate the classification. This was done to allow a more nuanced and robust approach to data analysis. Those in scope are highlighted in Tables B2 and B3.

Table B2. Organisational level of entities identified through questionnaires.

Cluster out of scope	A cluster of institutions with associated infrastructures, such as a campus, science park or university consortium, such as the N8 group of universities
Institution out of scope	An institution whose core purpose is greater than to operate a single infrastructure. Either the institution houses multiple infrastructures and/or it performs significant other functions, such as public engagement. Examples include universities and national labs
Coordinating infrastructure in scope	An infrastructure in its own right that coordinates other infrastructures within it. An example would be the Centre for Longitudinal Studies that also hosts four distinct cohort infrastructures. It differs from an institution in that it does not perform significant other functions. Many distributed ESFRI projects are coordinating infrastructures
Infrastructure in scope	Facilities, resources and services that are used by the research and innovation communities to conduct research and foster innovation in their fields and provide a distinct capability Infrastructures can be physical or virtual resources, or the facilities, instruments, tools and techniques that support them. They can be located at a single site, mobile or distributed across many places A single infrastructure can also be an institution, e.g. Diamond. It would be categorised as infrastructure if it did not perform significant other functions (e.g. teaching, outreach)
National Node in scope	National component parts distributed international infrastructures
Sub-nodes: Regional Node out of scope	Regional component parts of distributed national or international infrastructures
Local Node out of scope	Local component parts of national or international infrastructures

Table B3. Capability scope of entities identified through questionnaires.

International in scope	Only capability in the UK. Other similar capabilities may exist in other countries or it may be one of a kind globally. Differs from a national infrastructure in that it has an international reputation, with strong international draw
National in scope	One of only a handful of capabilities in the UK or the only one in the UK. Differs from an international capability by being more nationally focused, although it may have some international users or collaborate internationally
Regional sector analyses only	Infrastructure capability replicated in the UK at a regional level. It's likely to be the only one in the region, or one of a small number in the UK
Local out of scope	Infrastructure is one of several similar capabilities in a region (regions such as Wales or in the south-east of England). Out of scope for all analyses

Caveats on questionnaire data

No questionnaire will ever capture the totality of research and innovation infrastructures in the landscape. Some infrastructures may have missed the communications altogether. For some sectors, such as the social sciences, arts and humanities, the concept of an infrastructure is recent and less embedded, risking non-participation as a result of a lack of self-identification. Some of the largest infrastructures may have considered that they were so well understood there was no need to complete the questionnaire. We mitigated these biases by cross-referencing our engagement against listings such as ESFRI[24] and MERIL[45].

There is not an even spread of infrastructures across the six broad research and innovation sectors. Any overarching analyses of the landscape will be driven by sectors with the largest numbers of infrastructures (i.e. physical sciences and engineering and biological sciences, health and food) and whilst this gives the correct overall picture it should be remembered that it may not be representative of a particular sector. In terms of cross-sector comparisons, for questions with small sample sizes we have not drawn conclusions from small differences in the data.

We believe that whilst specific gaps may exist in the questionnaire data from missing individual infrastructures, there is representative coverage overall. Gaps identified after publication of the Initial Analysis report through sector analysis and stakeholder input were addressed, particularly in the space and clinical discipline areas.

Another source of potential bias arises from variation in infrastructures' scale and position in the organisational topology. In terms of scale there could be a bias if equal weighting was given to each infrastructure, for example whether it is the national archive (e.g. the British Library) or a smaller specialist one. Since the Initial Analysis was published we developed and applied the organisational and capability categorisation presented in Annex B to control for this and remove entries that were out of scope for this programme.

The quality of data generated by questionnaires can be variable. Questionnaires are subject to differences in understanding and interpretation, especially when language and terminology differ naturally between the broad sectors we targeted. To capture as broad a picture as possible, some questions were optional leading to variation in sample sizes and not every question could be posed in a way that was easy to analyse. Additionally, whilst we were careful in clarifying our criteria for engagement, we received completions from infrastructures that did not fit these or that were from a campus or an institution rather than from the infrastructures within them.

We controlled quality in a number of ways. Every entry was read and assessed against our criteria (Annex A). We identified and encouraged institutional responses to provide us with data for each of their infrastructures. Those failing any checks were not included in the analysis for this report. Reasons for exclusion are presented in Chapter 2, Figure 2.1.

During data exploration factual errors were corrected using information provided in explanatory fields or through further investigation, for example following misinterpretation of whether a funding source was public or private or by correcting typing errors. We also included the option of adding a supplementary secondary classification to each infrastructure. This did not overwrite the original data but instead allowed additional data exploration.

Acronyms and Abbreviations

AHRC	Arts and Humanities Research Council
AI	Artificial Intelligence
AIRTO	Association of Innovation, Research and Technology Organisations
AMRC	Advanced Manufacturing Research Centre
ATI	Alan Turing Institute
BAME	Black, Asian and minority ethnic backgrounds
BBSRC	Biotechnology and Biological Sciences Research Council
BGS	British Geological Survey
BH&F	Biological sciences, health and food
CCFE	Culham Centre for Fusion Energy
CCP5	Computational Collaboration Project No 5
CERN	Conseil Européen pour la Recherche Nucléaire (European Organisation for Nuclear Research)
CLF	Central Laser Facility
CLOSER	Cohort & Longitudinal Studies Enhancement Resources
COAST	Coastal, Ocean And Sediment Transport
Diamond	Diamond Light Source
ECMWF	European Centre for Medium-Range Weather Forecasts
E-INF	Computational and e-infrastructure
ELIXIR	European life science infrastructure for biological information
EMBL	European Molecular Biology Laboratory
EMBL-EBI	European Molecular Biology Laboratory - European Bioinformatics Institute
ENV	Environment
EPSRC	Engineering and Physical Sciences Research Council
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESRC	Economic and Social Research Council
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EU	European Union
EU-XFEL	European X-ray Free-Electron Laser Facility
FAAM	Facility for Airborne Atmospheric Measurements
FTE	Full Time Equivalent
G7	Group of Seven (Canada, France, Germany, Italy, Japan, the UK and the USA)
GLAM	Galleries, Libraries, Archives and Museums
HEI	Higher Education Institute
HESA	Higher Education Statistical Agency
HPC	High Performance Computing
ILL	Institute Laue-Langevin
IPERION CH	European research infrastructure for restoration and conservation of Cultural Heritage.
ISIS	ISIS Neutron and Muon Source
JANET	A high-speed network for the UK research and education community, provided by Jisc
JASMIN	Joint Analysis System Meeting Infrastructure Needs
JET	Joint European Torus
JWST	James Webb Space Telescope
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
MAST	Mega Amp Spherical Tokamak
MC2	Material and Chemical Characterisation Facility
MRC	Medical Research Council
N8	Collaboration of the eight most research intensive universities in northern England
NERC	Natural Environment Research Council
NIAB	National Institute of Agricultural Botany
NMR	Nuclear Magnetic Resonance
NNL	National Nuclear Laboratory
NNUF	National Nuclear User Facility
ONS	Office of National Statistics
ORE	Offshore renewable energy
PS&E	Physical sciences and engineering
PSRE	Public Sector Research Establishments
PV	Photovoltaic
R&D	Research and development
SSAH	Social sciences, arts and humanities
UCL	University College London
UKDS	UK Data Service
UK-RIHS	UK Research Infrastructure for Heritage Science
XML	Extensible Markup Language

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UK Research and Innovation