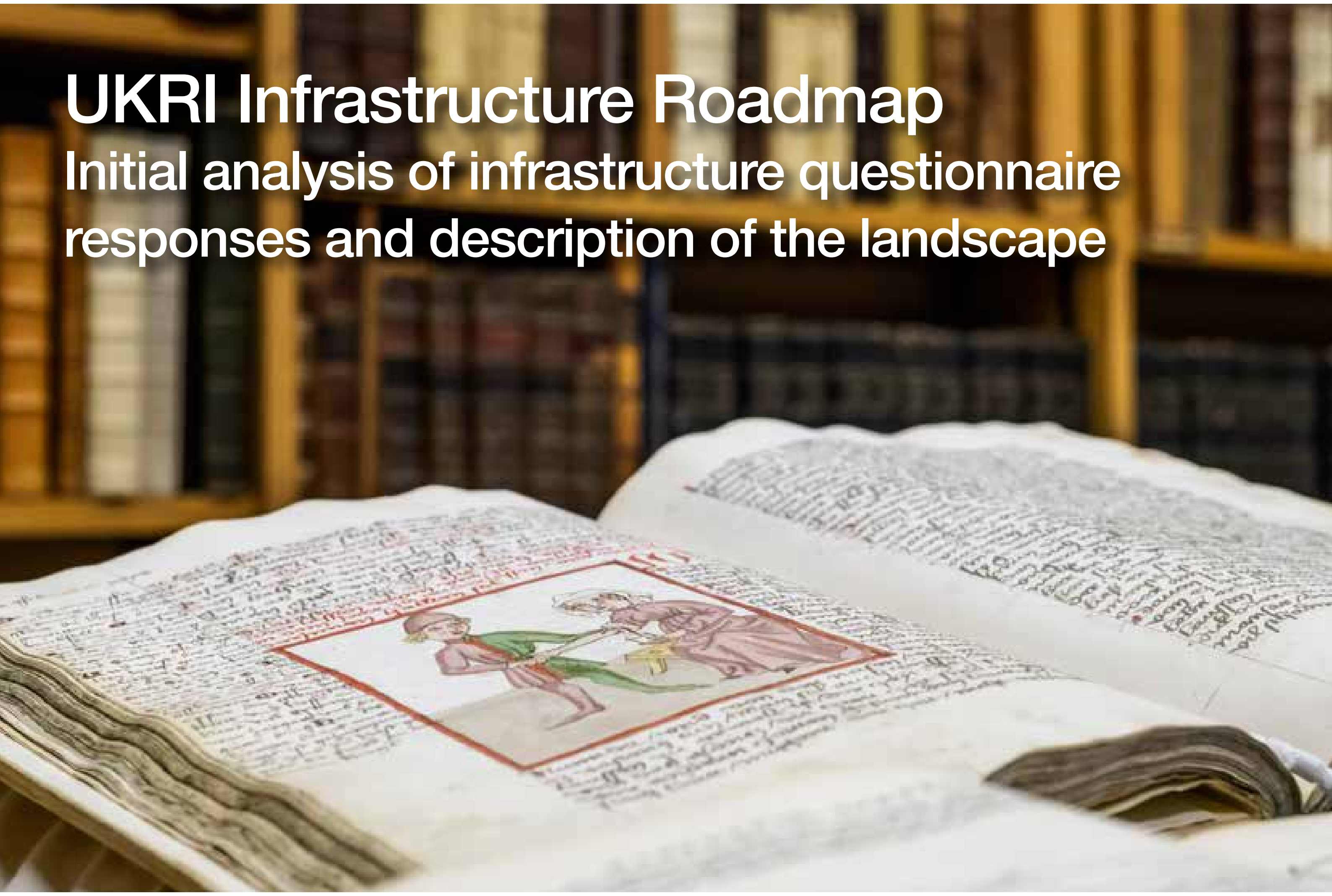
UK Research
and Innovation



UKRI Infrastructure Roadmap

Initial analysis of infrastructure questionnaire responses and description of the landscape

Contents

Foreword

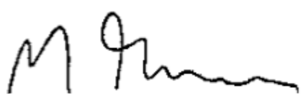
UK Research and Innovation (UKRI) has been commissioned by the Department of Business, Energy and Industrial Strategy (BEIS) to develop a research and innovation infrastructure roadmap. The programme is part of wider activity across government to develop a roadmap to raise investment in research and development (R&D) to 2.4% of GDP and within UKRI and its Councils to further develop its forward strategy[1]. It is intended to increase our understanding of the UK's current capability and guide future planning.

Understanding our current research and innovation infrastructure capability provides a solid foundation on which to build our roadmap for future planning, as is discussed in the parallel Progress Report[2] on emerging future themes. This report presents an initial analysis of the UK's current infrastructure. It draws heavily from two questionnaires conducted with over 800 existing infrastructures, supplemented with insight gained from consultation workshops and interviews with stakeholders. These span research disciplines and cut across the research and innovation spectrum.

The UK's global stature in research and innovation is underpinned by a long history of funding world class research and innovation infrastructure through private, charity and public mechanisms. This report includes publicly funded infrastructures from bodies such as UKRI and its councils, public sector organisations, other government departments and devolved administrations, but excludes infrastructure solely funded through private or charitable means. We have captured infrastructures that provide access to researchers and innovators beyond the host institution, whether they are physically located in the UK, overseas, in space or provided digitally or remotely. Infrastructures are typically large, costly, and/or complex, driving the need for collaboration and this report focusses on those that provide at least a regional or national capability.

This is the first time that an exercise of this breadth and type has been attempted in the UK. The questionnaire campaign we developed had high but not universal uptake and we recognise that it has not been possible to capture every infrastructure during this initial phase. The roadmap team is compiling a list of infrastructures to further interact with over winter 2019 and information about such omissions should be communicated to **infrastructure@ukri.org**

We are very grateful for the significant questionnaire input that over 800 infrastructure stakeholders have given to the process so far, as well as to those participating in workshops and interviews. We hope that by sharing these emerging findings we will further engage with the community to identify gaps in our knowledge of the infrastructure landscape and improve our coverage for the final programme publications in 2019.



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

Executive summary

This report is an initial analysis of the landscape of research and innovation infrastructures (infrastructures) available to UK researchers and innovators. It is presented as an indicator of our current understanding. It is designed to be used to catalyse discussion and further engagement during winter 2018/19, which will feed into the final analysis that we produce of the landscape in spring 2019.

- The UK has a rich and diverse landscape of research and innovation infrastructures. Our questionnaires uncovered 712 infrastructures that had at least a national significance and a further 43 with a regional significance. They come in many different guises, such as libraries, telescopes, databases, biobanks, environmental observatories and synchrotrons

- Most infrastructures are single sited, hosted within UK higher education institutions and have an expected lifecycle of at least 25 years. Many of the infrastructures are less than 5 years old

- The largest sectors within our survey were the PS&E and BH&F that cover a broad range of disciplinary areas. However, research and innovation is rarely single-domain led and infrastructures identified with three sectors on average. E-infrastructure has a pervasive role across all sectors

- The location of infrastructures within the UK largely follows the distribution of national research and innovation funding, however, this varies by sector. Infrastructures in the PS&E, Environment and Energy sectors are more dispersed across the UK than the other sectors. Some infrastructures have no fixed location, such as ships, planes or satellites and some have functions distributed across a number of nodes. The UK is a partner in almost 50 international infrastructures in at least 30 countries around the world, infrastructures such as EMSO, CESSDA, LIGO and ESO

- Infrastructures are inherently collaborative and promote international cooperation. There is a constant flow of users seeking access to the best facilities wherever they are. In the UK 38% of users of infrastructures come from outside the UK and 88% of infrastructures have an international user base. Specialised staff are also attracted from across the world with 25% of staff coming from outside the UK

- This analysis focuses on infrastructures that are reliant on public funding for both set up and operation. Over half of infrastructures are reliant on public funding to cover at least 70% of their costs. Many rely on funds from multiple sources within the public sector such as research councils, government departments, local government or devolved funding agencies. Other sources include EU funding, industry or charitable support and commercial income

- Over 75% of infrastructures work with business to some degree. This engagement spans the economy - the top industrial sectors mentioned by infrastructures include health services, energy sector, agriculture, manufacturing sectors, computing and communications, transports sectors and services sector. Contribution to public policy was highly cited across the landscape and particularly in SSAH, Energy and Environment

- UK infrastructures in our questionaire estimate that they employ around 34,000 staff (FTE) with a mean headcount of around 50 FTEs per infrastructure. Staff roles are balanced between those focused primarily on research (37%), technical roles (34%) and management/ administration (29%). Compared to UK HEIs infrastructures tended to employ fewer women and slightly fewer staff from BAME backgrounds but have a greater reliance on overseas staff (25% compared to 20% of all HEI staff)

- The critical barriers to maximising the benefits of infrastructures cited in responses were concerns about funding (including the short term nature of funding), uncertainty over EU exit, shortages of personnel and skills (including retention and succession issues). Common mitigations included diversification of funding streams, actively pursuing partnerships and collaborations and a range of staffing or training strategies

Since this is the first attempt to map the UK's research and innovation infrastructure landscape across all the disciplines represented here we recognise there will be gaps in our data. Over the final months of the roadmap programme we will be addressing critical gaps in our coverage of infrastructures and conducting further analysis. The roadmap team is compiling a list of infrastructures to further interact with over winter 2019 and information about omissions should be communicated to **infrastructure@ukri.org**

Chapter 1: Context and approach

The term ‘infrastructure’ can be interpreted in many ways. For the purposes of this programme we have adapted the definition used by ESFRI and the EU Framework Programme[3].

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

We 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
- Energy
- Environmental sciences
- Physical sciences and engineering
- Social sciences, arts and humanities
- Computational and e-infrastructures

However, few infrastructures support a single sector even when using definitions as broad as the above six and we recognise that many infrastructures are multidisciplinary or interdisciplinary.

Although many international roadmapping exercises have followed a similar approach for research infrastructures there is currently no commonly accepted definition of ‘innovation infrastructure’. Some consider innovation in its broadest sense including people, polices and processes, others focus more on physical buildings and assets[4,5,6] For the purpose of this exercise 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 may include, for example infrastructure aimed primarily at industry and set up to explicitly foster and commercialise innovation, such as the Catapult Centres, Innovation and Knowledge Centres, Centres for Agricultural Innovation and Innovation Centres in Scotland: research and innovation campuses and infrastructure where academic researchers and business collaborate and innovation focused activities based within universities or public sector research establishments.

A full description of the scope and criteria used for this roadmap can be found in Annex A. We have focused our work on infrastructure funded directly through public sector research and innovation funders. This means we have not captured capability funded solely through private or charitable means, or a comprehensive picture of wider public sector investments such as public health establishments whose primary purpose is treatment of patients but where high quality research and innovation may also be undertaken. However, we recognise this wider capability is also vital to the UK and a critical part of the capability in key sectors and subsequent iterations of the programme could build on this initial analysis to consider this broader landscape.

As with most roadmapping exercises undertaken in other countries, we have focused on activities that are open to a wide range of users to undertake excellent research and innovation. We have included infrastructures that have at least a regional significance to understand the breadth of capability available in each sector, but limited our higher-level picture of the landscape to international and national level activities to align with and inform the parallel progress report[2]. We are not seeking to capture or explore regional or local needs for infrastructure but recognise the importance of underpinning investment in smaller and mid-range facilities within universities and public sector research establishments.

Research and innovation infrastructures are strategically valuable assets for the UK, underpinning cutting edge research and innovation and making a key contribution to economic activity. They are a key instrument in bringing together stakeholders to tackle societal challenges. Media interest in infrastructures such as the Large Hadron Collider inspires and excites the public and the next generation[7]. 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[8]. They therefore sit in the centre of the knowledge triangle of research, education and innovation.

Infrastructures come in many different guises, such as libraries, telescopes, databases, biobanks, environmental observatories and synchrotrons. They can be classified into broad categories and may be accessed in person, remotely or via digital or virtual mechanisms (Figure 1.1):

- Single-site/single entity
- Distributed or grouped - geographically distributed facilities or resources
- Virtual or digital

Many grouped or distributed infrastructures operate 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 grouped infrastructures have equal partnerships rather than a hierarchical model, typified by those operating as a network across the UK's devolved administrations. A few infrastructures cluster with a coordinating infrastructure that provides organisational functions, such as the Centre for Longitudinal Studies with the National Child Development Study (NCDS), 1970, Millennium and Next Steps cohort studies, all of which are infrastructures in their own right.

This report is an initial analysis of the landscape of infrastructures available to UK researchers and innovators and supported through public funding. It is neither fully comprehensive in its coverage of every available infrastructure nor in the breadth or depth of the subsequent analysis, thus it is not an early draft of the final product. It is presented as an indicator of our current understanding to catalyse discussion and further engagement during winter 2018/19, which will feed into the final analysis that we produce of the landscape in spring 2019.

We are considering infrastructure with a range of primary functions but recognise that this capability is interdependent and connected (Figure 1.2).

The lifecycle of an infrastructure consists of different phases that each vary in duration. After identifying a need, the concept for the infrastructure is developed during a design phase. The following preparatory phase develops the legal and contractual frameworks prior to implementation of the infrastructure (for example, construction of a physical facility). These phases can be considered pre-operational (concept development, design and preparation, implementation/construction). A period of operations follows that typically lasts in the order of several decades. This can include periodic major upgrades to the infrastructure or the infrastructure may evolve incrementally as technology and demand changes. Finally, the infrastructure is either decommissioned and terminated or re-purposed[9].

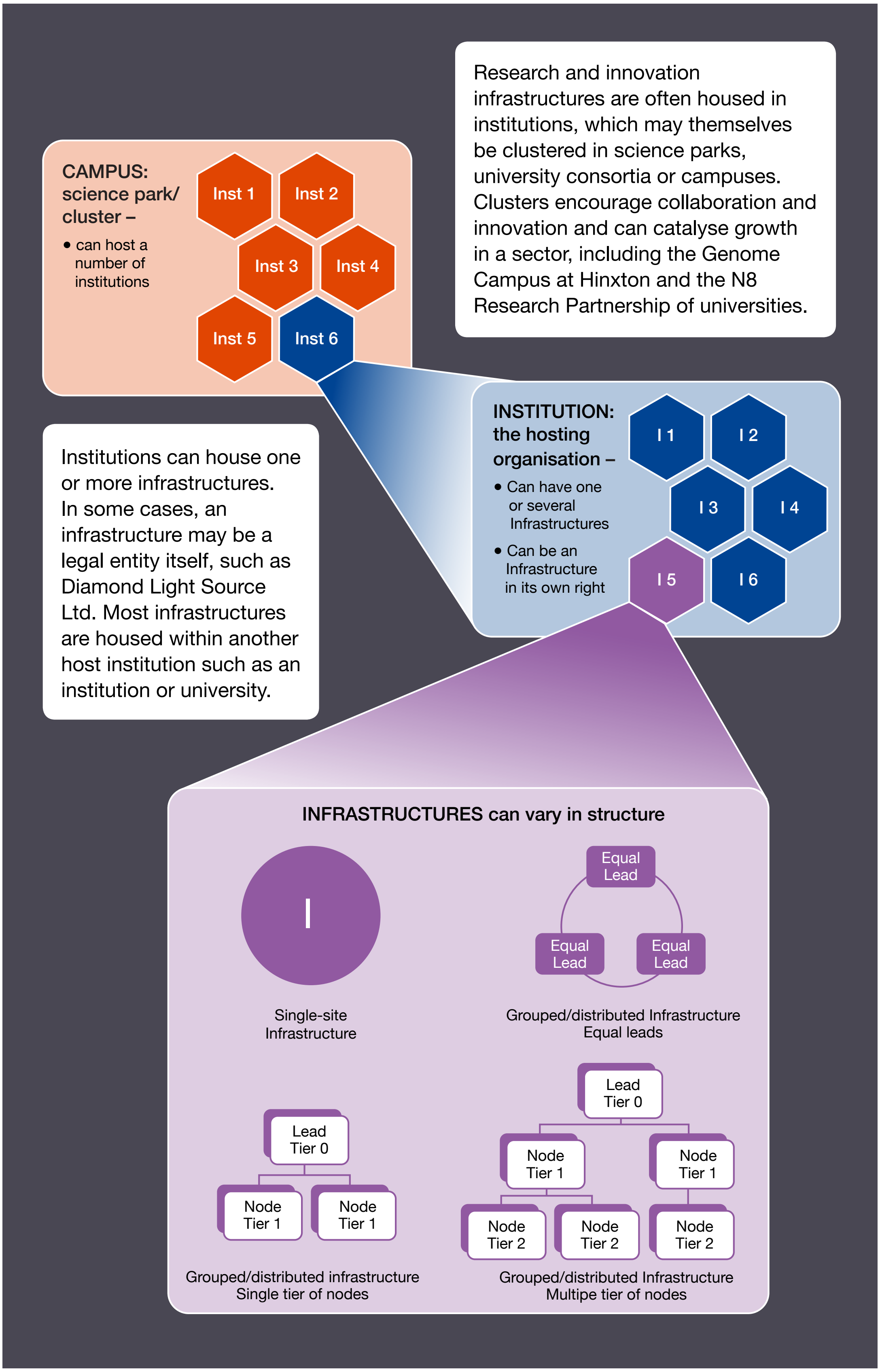


Figure 1.1. Organisational topology of research and innovation infrastructures.

Clusters (e.g. campuses, science parks, university consortia)

The Harwell Campus in Oxfordshire is developing three clusters built around colocation with multidisciplinary infrastructures such as CLF, ISIS, Diamond, Emerald and a suite of satellite testing facilities at RAL Space. The Space Cluster is the gateway to the UK Space Sector. It also benefits from the presence of other leading public space organisations, including the European Space Agency Satellite Applications Catapult and UK Space Agency. These are joined by global space companies such as Airbus and Lockheed Martin alongside 80 SMEs and start-ups.

Satellite testing Credit: UKRI STFC

Institution

The University of Edinburgh hosts a number of different infrastructures. Examples include:

- Software Sustainability Institute
- The Cockburn Geological Museum
- Roslin Innovation Centre
- National Creutzfeldt Jakob Disease Research and Surveillance Unit
- Scottish Longitudinal Study
- Edinburgh Centre for Carbon Innovation
- Scottish Microelectronics Centre
- Wide-Field Astronomy Unit

Photo courtesy of the Roslin Institute, University of Edinburgh

Single-entity infrastructure

The Medicines Discovery Catapult Ltd is a national facility for collaborative R&D exploring and developing new approaches to the discovery and proof of well targeted medicines, diagnostics and biomarkers. It brings together a fragmented UK sector of industry, academia, charities, finance and others to turn research into new high value products.

Distributed infrastructure

EPOS, the European Plate Observing System, is a distributed infrastructure for solid earth science to prepare for geo-hazards and responsibly manage the subsurface for infrastructure development, waste storage and the use of Earth's resources. The British Geological Survey hosts the UK node and the Integrated Core Service Central Hub for the European project that is headquartered in Italy.

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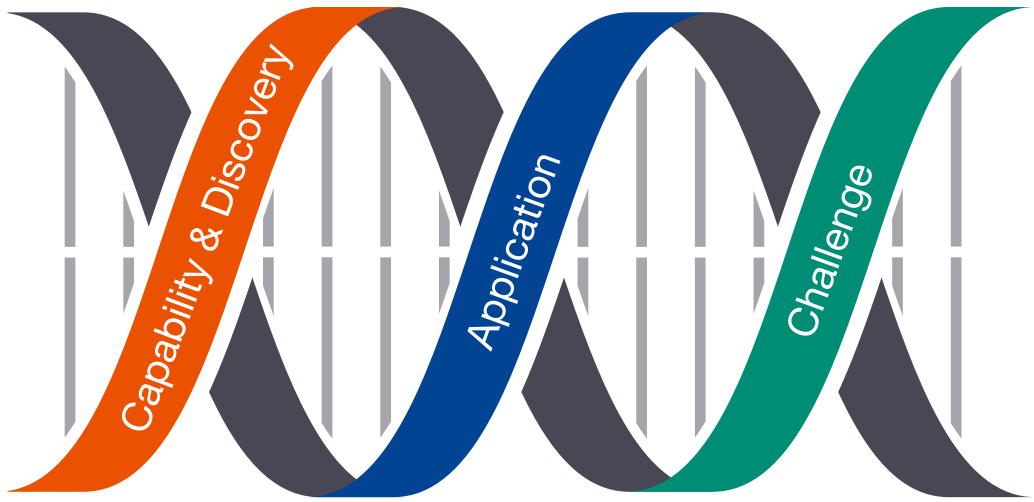
Our picture of the current landscape draws heavily from information gathered by conducting two questionnaires with infrastructures, supplemented by knowledge gleaned from interviews and workshops (see Annex B for detailed methodology). Questionnaires were designed to interact with existing and planned infrastructures at all stages of their lifecycle. Questionnaire one was broad in scope and used a combination of optional and mandatory questions to maximise uptake whilst providing a minimum baseline of data. The second questionnaire was optional and open to any infrastructures who had completed questionnaire one. It interrogated a few areas in greater depth and covered some new themes following early analysis of questionnaire one responses.

A combination of methods were used to identify and target infrastructures for the questionnaire. Infrastructures identified via a desk study and consultation were invited directly to complete the questionnaire. Whilst this exercise revealed almost 700 infrastructures, a second campaign led by higher education funding councils approached Higher Education Institutions (HEIs) and other research and innovation establishments to further disseminate the opportunity to participate and to target those not already identified. Conducting a questionnaire with infrastructures allowed us to gather the information required for the landscape analysis and reach the broadest 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.

Since this is the first attempt to map the UK's research and innovation infrastructure landscape across this breadth there is no



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

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

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

Figure 1.2. Infrastructures may have different primary functions but are interconnected.

established baseline against which our coverage can be assessed. No questionnaire will ever capture the totality of its targets. Additionally, questionnaires have limitations or variations in the quality of data that they capture due to differences in understanding and interpretation. Chapter 2 discusses the approach we have taken to mitigate and manage risks in data quality and quantity.

One of the purposes of this initial landscape analysis is to further engage with the community to identify gaps in our knowledge of the infrastructure landscape and improve our coverage for the final programme publications in 2019. The roadmap team is compiling a list of infrastructures to further interact with over winter 2019 and information about such omissions should be communicated to **infrastructure@ukri.org**

Chapter 2: Landscape overview

The UK has a rich and diverse landscape of research and innovation infrastructures. The questionnaires uncovered 712 infrastructures that had at least a national significance and a further 43 with a regional significance. For the purposes of this overview (Chapter 2) discussions will be limited to the 712 infrastructures of national significance and above. The sector chapters that follow this chapter draw on the broader sample of 755 infrastructures of regional significance or greater for their quantitative analysis, supplemented by additional insight gathered by other mechanisms in their narrative for a comprehensive discussion of their areas.

Questionnaire limitations and potential bias

Given that engagement with the UK's infrastructures at this scale has never been attempted before, obtaining baseline survey data from 712 national and international infrastructures is a healthy achievement and provides appropriate information for this report. However, no questionnaire will ever engage every infrastructure and this report, whilst broad, does not represent the entire UK landscape. Many factors may have influenced the quality and quantity of information we were able to gather:

- There will have been differences in the motivation and encouragement of different groups of infrastructures to engage and complete our questionnaires
- The sample and questionnaire data will also have been affected by 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 a number of steps to minimise or mitigate the risks that variation in the quality or quantity of data would cause a bias in analysis of the landscape. In summary:

- Validation of engagement coverage by cross-referencing existing catalogues (e.g. MERIL, ESFRI) and other stakeholder groups
- Development of an organisational topology model to understand the type of infrastructure entity (see Chapter 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 question is drawn from the same sample size (e.g. 712 for overview, 755 for sector chapters). However, 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 are made where differences are small or when not backed up by additional insight (e.g. consultation or interviews)
- Validation of data against other known sources where possible

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. A detailed breakdown of possible sources of bias and their mitigations can be found in Annex B: Methodology.

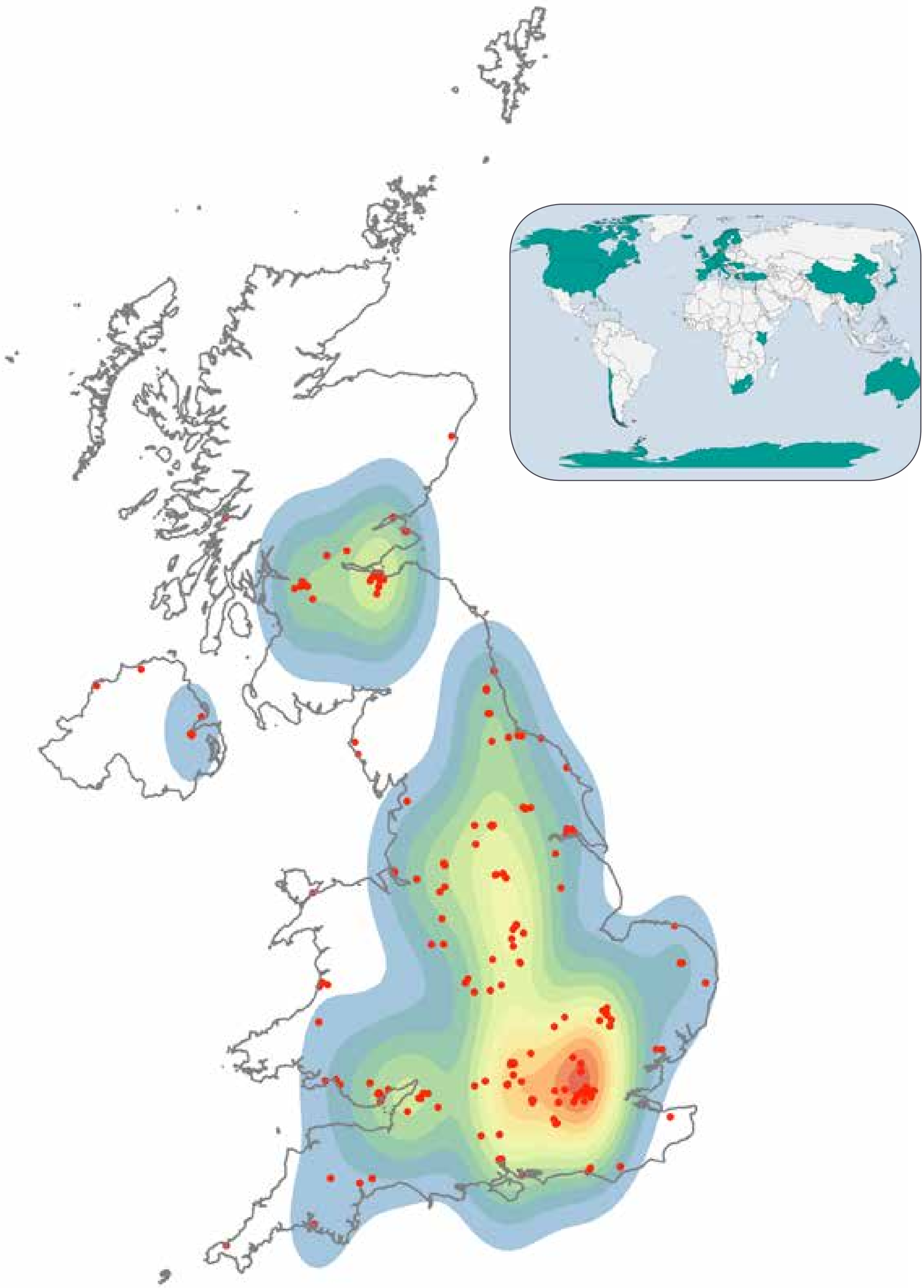


Figure 2.1. Geographical distribution of infrastructures available to researchers and innovators in the UK and (inset) globally. The UK map provides a splash of colour around areas with infrastructures, with high density areas highlighted red through to low density areas highlighted blue/white. There is smoothing across the different areas which is why the image flows. Dots can represent individual infrastructures or clusters of infrastructures at the same location. Countries hosting an infrastructure accessible to UK researchers and innovators are coloured blue on the world map (note that some countries host more than one infrastructure).

Geographical distribution of infrastructures

Infrastructures accessible to UK researchers and innovators are located in every region of the UK and in at least 30 countries outside of it (e.g. through UK funding or membership partnerships). Figure 2.1 shows a high density of infrastructures in the South East of England with further concentrations through the M4 corridor, the Midlands, North West and Edinburgh-Glasgow corridor of Scotland. As 87% of infrastructures are housed within other institutions, primarily HEIs, the pattern of infrastructure distribution follows the general pattern of national research and innovation funding. Some infrastructures have no fixed location, such as ships, planes and satellites, or have functions evenly distributed between component nodes such that declaring a single load location of the infrastructure is not possible. For mobile infrastructures the map depicts the location of their administrative headquarters (e.g. the research ship RRS Ernest Shackleton is operated by the British Antarctic Survey in Cambridge). If no lead location could be demonstrated for a distributed infrastructure the location of the infrastructure has been omitted from this map.

Sector coverage

The research and innovation landscape has been divided into six broad thematic domains based on the accepted ESFRI methodology[10].

These are:

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

Each of these sectors can be further broken down into sub-domains where appropriate as presented within chapters 3-8. Research and innovation infrastructures occur both within these broad sectors and across sector borders. Each sector is different in size and in many of its characteristics.

Infrastructures were asked to select the primary sector they identified with (Figure 2.2). The PS&E and BH&F sectors are the two sectors with the largest proportion of infrastructures, 33% and 29% 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 E-infrastructure. The E-infrastructure sector had previously conducted an annual survey of e-infrastructure facilities and this questionnaire reached most of the infrastructures that are known to exist from this baseline.

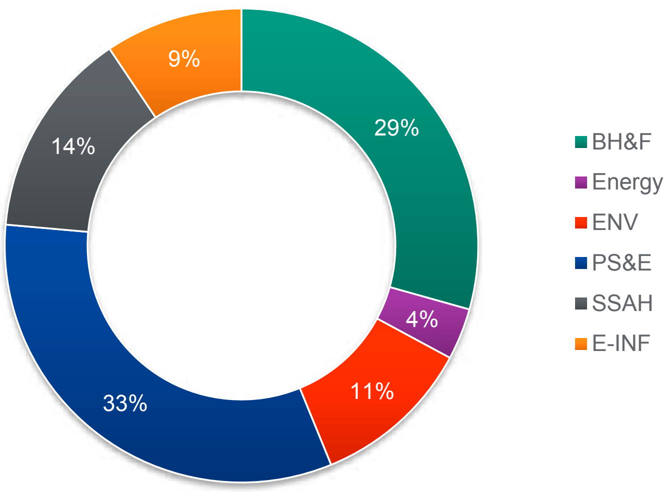
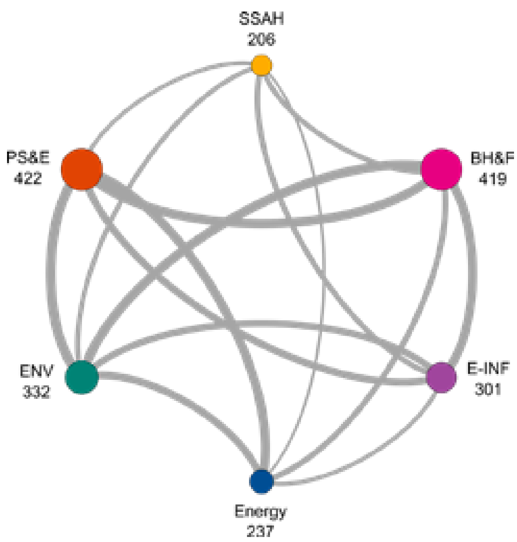


Figure 2.2. The distribution of research and innovation infrastructures according to the primary sector they identified with.

The questionnaire reached 25 national and international infrastructures in the Energy sector. As this is a comparatively small number additional methods of engagement were employed to discover the true size of the Energy sector. Consultations uncovered a further 32 infrastructures, thus whilst the questionnaire data for Energy infrastructures is a small sample of the entire dataset, it covers almost half of the infrastructure landscape. E-infrastructure can be a primary sector in its own right, or it can be an important tool that other sectors rely on. For infrastructures that did not list E-infrastructure as their primary sector around two-thirds of infrastructures acknowledged its importance as a tool.

Modern research and innovation is rarely single-domain led and most infrastructures we engaged with identified with more than one sector that they work with (mean = 2.7 sectors, i.e. one or two sectors in addition to the sector they identify with as their primary domain). The number of sectors engaged with varied across the infrastructures depending on their primary sector identity (Figure 2.3). Infrastructures in the e-infrastructure sector had the broadest reach, with 60% identifying with four or more domains, which reflects the pervasive role of many e-infrastructures. The Environmental sector was the next broadest sector with 65% identifying with three or more sectors.

When infrastructures were asked to identify all sectors that they identified with, the PS&E and BH&F were the most common sectors selected (Figure 2.4). There were overlaps between all sectors demonstrating the multidisciplinary nature of research and innovation at infrastructures.



The plot shows the overlaps between sector coverage.

The size of the nodes relates to the number of responses that selected each sector.

The thickness of the edges relates to the extent of co-occurrence (overlap) between sectors selected.

Figure 2.4. Overlaps between the sectors selected in infrastructures that identified with more than one sector.

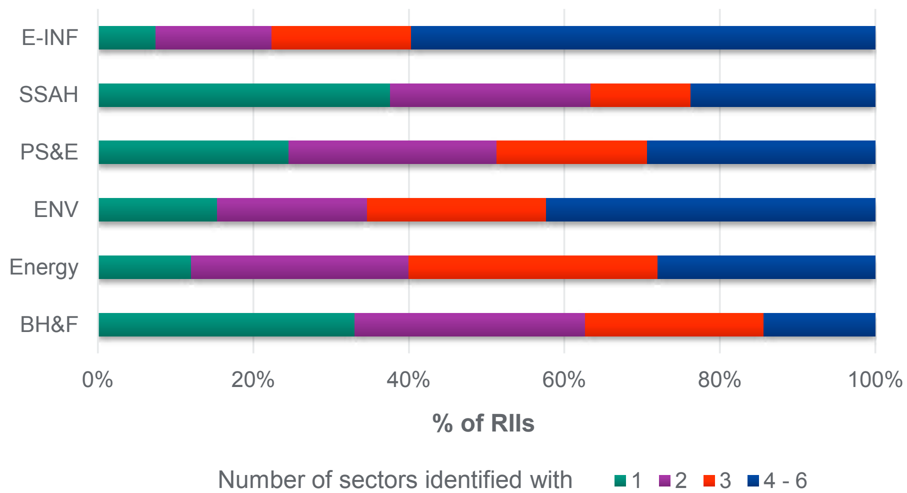


Figure 2.3. The number of sectors infrastructures identify with based on their primary sector identification.

Legal/organisational structure

Research and innovation infrastructures come in many different forms that can broadly be categorised into the following:

- Single-site/single entity infrastructures are central facilities geographically localised in a single site, such as a museum, an observatory housing telescopes or a synchrotron
- Distributed or grouped infrastructures may consist of nodes linked together that perform as a single entity. What sets a distributed infrastructure apart from a network is the use of central coordination and single access point and policy to facilitate use
- Virtual infrastructures are infrastructures accessed digitally, such as data infrastructures
- A hybrid of two or more options

There are also groups of infrastructures that federate together under a coordinating entity or infrastructure to function as one, adding additional capability.

Single-site infrastructures were the most common form of infrastructure (64%) that engaged in our questionnaire (Figure 2.5). The organisational structure varied between sectors and differences are discussed fully in the individual sector chapters that follow.

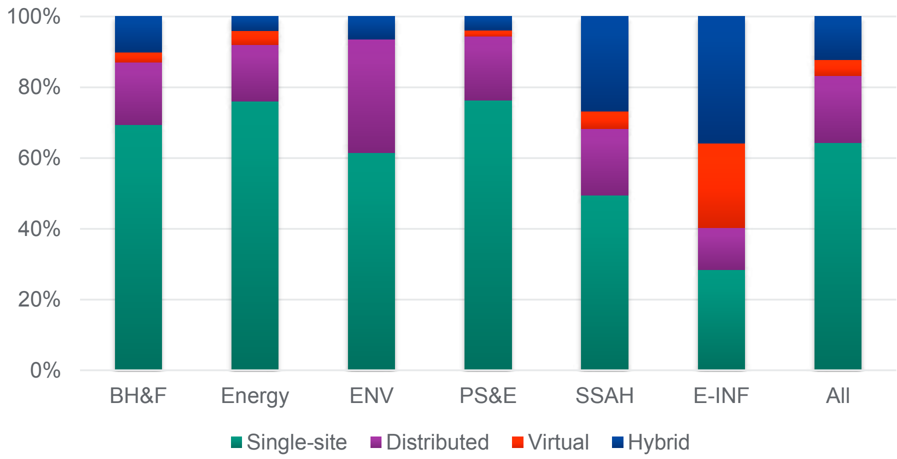


Figure 2.5. The percentage of infrastructures operating under different organisational models.

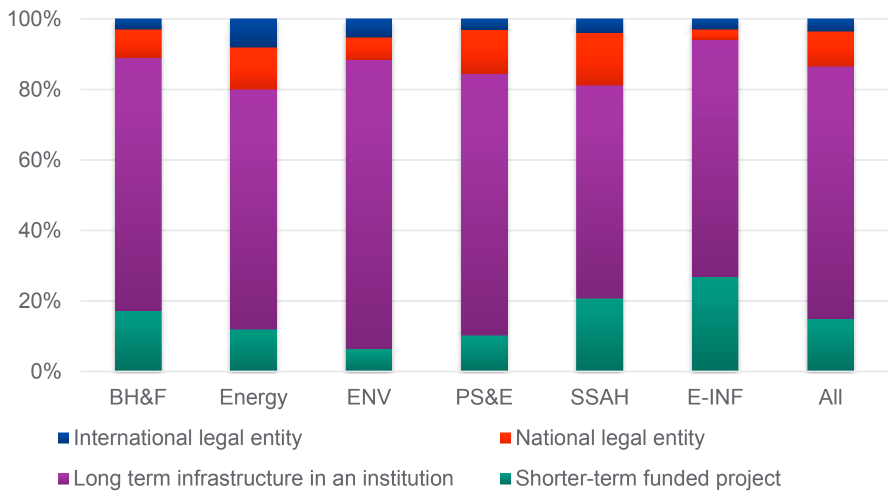


Figure 2.6. The legal structure of research and innovation infrastructures.

Most infrastructures (87%) were housed within another institution, mainly UK based HEIs, and were not established as independent legal entities (Figure 2.6). This is consistent with patterns of the general distribution of research and innovation funding in the UK. Embedding infrastructures within HEIs and other institutions can also facilitate access to wider university capabilities including skilled students and staff. Where infrastructures are established as separate legal entities this is usually due to the nature of the research and innovation work undertaken e.g. the scale of activity, security issues or the complexity of governance and partnerships involved. Legal organisational structures also reflect the history of particular disciplines. Some disciplines have long established institutions for research and innovation outside of the university sector; others are established with governance that enables collaboration or co-location with particular user bases e.g. with businesses or parts of the public sector.

Lifecycle and age

The concept of the life cycle of research and innovation infrastructures is now widely accepted and a fairly common approach has been adopted by different organisations across all sectors[11,12]. The landscape has significantly changed since first wave of modern infrastructures were established out of laboratories in physical sciences (e.g. CERN, ESO). Since then there has been an emergence of big user facilities spanning research domains, such as materials science and structural biology, followed by big data driven infrastructures, often distributed or virtual in nature.

The increasing complexity and cost of infrastructures have all contributed to shape the new concept of a research and innovation infrastructure in a way that is understood and applied in all sectors. The current life cycle is the result of this evolution, which has taken place side by side with the development of new infrastructures.

There is now a common understanding that infrastructures typically go through various phases in their life time, from **concept development and design**, to **preparation, implementation** and **operation**, and in some cases to **termination/decommissioning** or alternatively to an **update**, **re-orientation** or **re-purpose** of their scientific mission (see progress report[2] for a fuller explanation). Certain types of infrastructures, such as cohort studies, continue to expand over time and their value increases as data accumulates. Depending on the sector and size of the infrastructure the design phase may require scoping studies to refine design and re-risk construction. Similarly, the early stages can be more fluid or more fixed, and some infrastructures can move through these

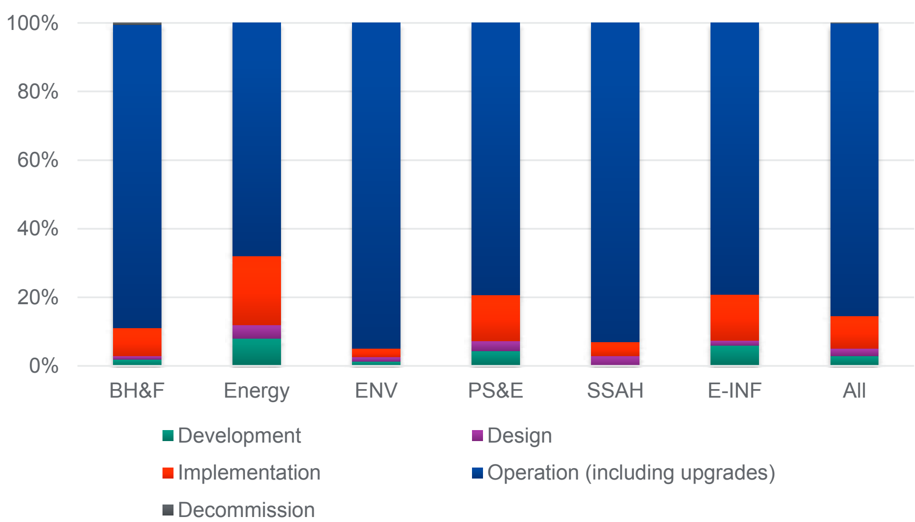


Figure 2.7. A comparison of the lifecycle stages of infrastructures in each sector.

phases in parallel, e.g. preparing their legal and business models whilst designing the infrastructure.

The life cycle of infrastructures is interlinked with their long-term sustainability and vision. These are prerequisites to the successful and sustainable operation of the infrastructure. There is a great consensus in that funding is not the only sustainability aspect in the life cycle of infrastructures and that robustness in their technical development and access models, their management, organisation and governance, and their human resources policy, are all crucial to the life of an infrastructure as much as it is the budget to establish and run the infrastructure.

Overall, 85% of infrastructures engaging in our questionnaire are in the operational phase (Figure 2.7 – All bar). The operational phase is typically the longest phase in the life cycle as, in general, most infrastructures expect to have an operational lifespan of over 25 years. This result therefore recognises that there is an established landscape of infrastructures in all sectors in the UK providing access and services to the research and innovation community. The Environmental and SSAH sectors have the greatest proportion of their infrastructures in operational phases.

The early phases of design, preparation and implementation are represented by 15% of infrastructures across all sectors, indicating an active renewal of the landscape with the emergence of new infrastructures. Some sectors appear more prominent in their representation at these early phases, such as Energy (Figure 2.7). There could be several factors influencing this result - the nature of the sector, the rate of technology turn over, variation in drivers (e.g. renewable energy) and the resultant investment in new infrastructures, and potential differences in awareness and/or responsiveness of infrastructures in different phases of development.

There was only a single response from an infrastructure in the decommissioning/ termination stage (BH&F sector). The termination phase can be a long process but can also lead to routes other than shutting down the infrastructure, such as re-purposing. This could simply indicate that at this specific moment there is only one infrastructure in the process of shutting down, as infrastructures may not have classified their lifecycle stage as termination if they were in the process of, or considering, re-purposing. There might be other cases for which decisions have not yet been taken. There is also the possibility of a bias against inclination to engage in the questionnaire for infrastructures that are at this terminal stage because they may consider their input less valuable or have less motivation to participate. Overall, there needs

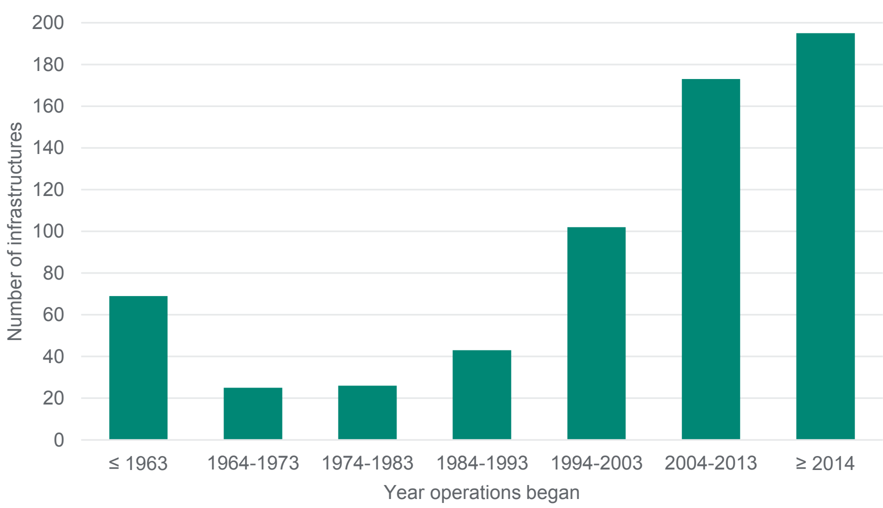


Figure 2.8. The distribution of infrastructures according to the period in which they commenced operations.

to be full understanding and recognition of the termination phase across all sectors. The more this phase is planned and articulated, the more robust the life cycle and sustainability of the individual infrastructure and the landscape overall.

There are more new infrastructures (less than 5 years old) than in any other category (Figure 2.8). 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 in existing fields. There might be a higher level of responsiveness from new infrastructures that by the very nature of obtaining funding have recent engagement with funders compared with infrastructures that have been established for many years. Additionally, 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 infrastructures would consolidate and be taken forward in the longer term.

The expected operational lifecycle of infrastructures varied according to the organisational and legal model of the infrastructure (Figure 2.9). Infrastructures established as legal entities (national and international) have longer expected operational lifespans than those housed in other institutions. Fewer infrastructures reliant on short-term funding have an expected operational lifespan of over 25 years than infrastructures in other organisational and legal structures.

There is a need for continued effort in understanding the life cycle 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 to respond to new developments and is holistic in its approach to sustainability.

International collaboration and participation

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. Research and innovation in the UK enjoys an internationally recognised status and has succeeded through engaging with the best organisations, infrastructures, researchers and innovators around the world. Research and innovation require the sharing of knowledge, expertise, data and capability across organisations, borders and continents. The research infrastructure communities in all fields contribute heavily to the UK's global

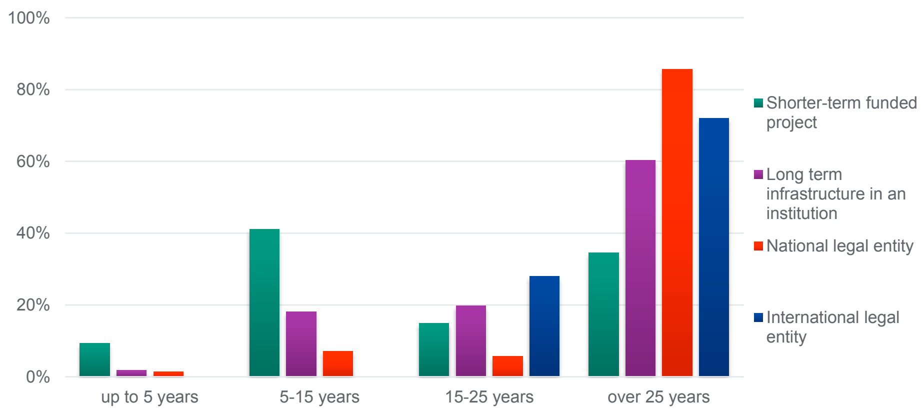


Figure 2.9. The percentage of infrastructures with expected operational lifespans from up to 5 years to more than 25 years grouped according to their legal organisational structure.

status through a long history of collaborative working and international engagement.

The challenges and threats facing society today do not recognise national boundaries and the collaborative nature of infrastructures alongside their intrinsic long term lifespan enables them to be well positioned to tackle these problems. 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 infrastructures that otherwise would not be affordable. Forty-eight infrastructures that engaged in the questionnaire were located outside the UK. Proportionately more of these were in the PS&E sector compared to other sectors (Figure 2.10). PS&E is characterised by having more of the very large, expensive physical infrastructures that are beyond the scope of a single nation to deliver (e.g. particle accelerators, telescopes).

Eighty-four percent of infrastructures collaborated with other infrastructures or organisations internationally. Infrastructures can also be effective assets for science diplomacy.

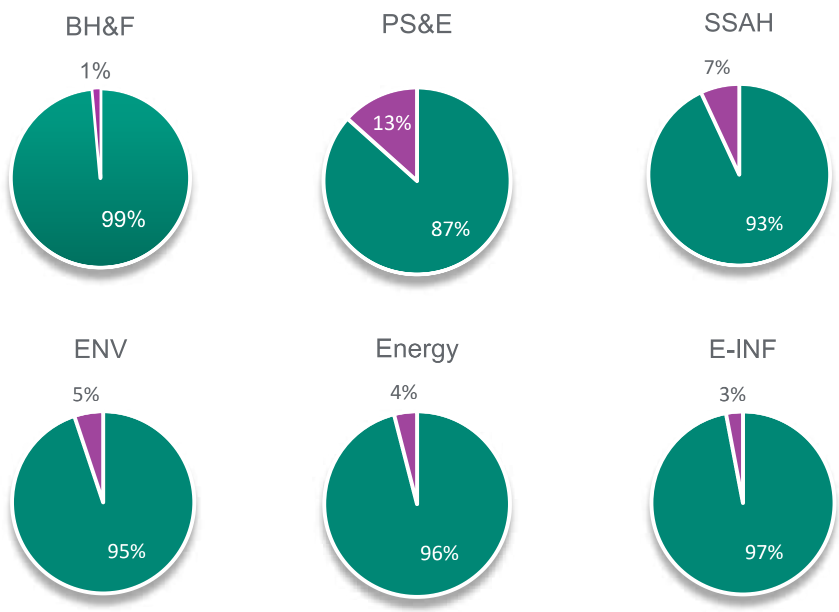


Figure 2.10. The number of infrastructures located within the UK (green) and outside the UK (purple).

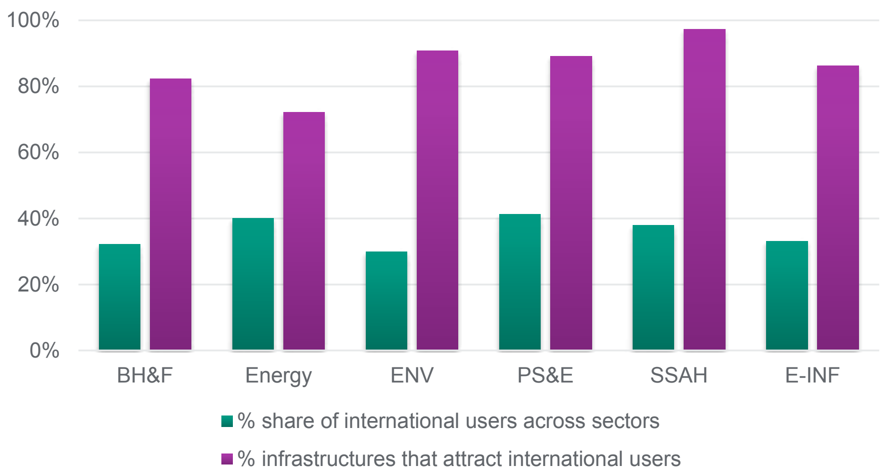


Figure 2.11. Attraction of UK-based infrastructures to international users based on their primary sector.

In the infrastructure international landscape there is a constant flow of users seeking access to the best facilities wherever they are. In the UK 38% of individual users of infrastructures come from outside the UK and 88% of infrastructures have an international user base (Figure 2.11). Thirty-nine percent of infrastructures consider that there will be a change in demand by the user-base which is likely to be more internationally biased than today. The Energy sector envisages the strongest increase in demand with 63% of infrastructures reporting an expectation of greater international use, possibly driven from lower current international user numbers compared to other sectors.

The collaborative and international nature of infrastructures and their need for specialist skills that are in limited supply mobilises talent across the world. Infrastructures in the UK attract significant talent from outside the UK (25% of staff). Infrastructures in E-infrastructure are most reliant on non-UK staff (38%) and only PS&E has fewer than one in five staff from outside the UK (18% of staff). The (non-UK) EU and EEA are the largest contributor (63%) of non-UK staff based at infrastructures in the UK. Both the operation of the UK's infrastructures and the global research status of the UK rely on the ability to attract and retain talent in technical, research and leadership areas. Attracting talent builds pools of skills, trains the next generation of researchers and innovators whilst accelerating advances in research and technology.

Sources of funding

The focus of this report is on infrastructures with a reliance on public sources of funding for establishment and/or operations. We have not included infrastructures that stated that they did not rely on public funds though recognise that there may be important components of the UKs overall capability that are funded through charitable and private means.

Our results demonstrate that there is a great reliance on public funding to set up an infrastructure. The reliance on public sources continues for operational costs with over half of infrastructures reliant on public funding to cover at least 70% of their costs (Figure 2.12). This is likely to be an underestimation because three quarters of infrastructures are based in institutions such as HEIs and reliant on HEI funding for a proportion of their costs, for which attribution of funding source can be challenging to quantify precisely.

The degree of reliance on public funds varies across the sectors. Fifty-three percent of environmental sector infrastructures were reliant on public funds for more than 90% of their costs, compared to 38% for Energy infrastructures and PS&E infrastructures. Operating costs are funded mostly through UK sources of public funding (Figure 2.13).

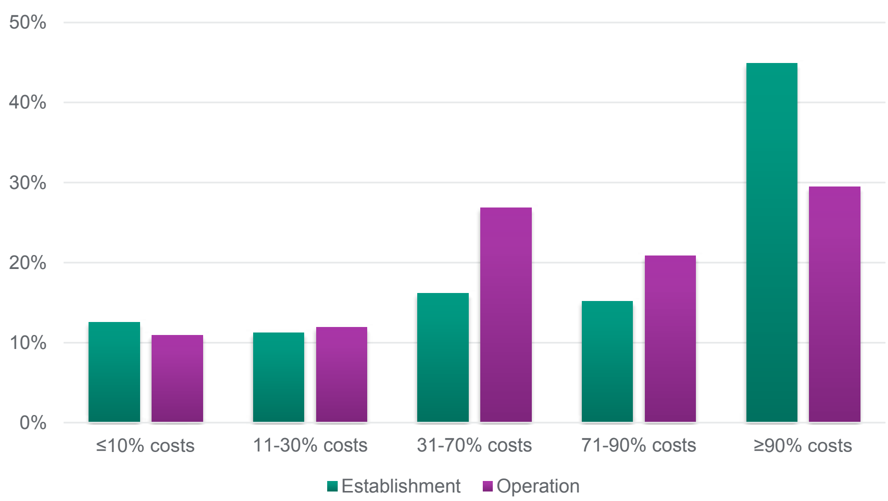


Figure 2.12. The degree of reliance on public funding for the establishment and operations of infrastructures.

Where further information was given about the 'other' sources of operational funding, this was split between commercial activity to generate income, industry and charity funding for projects, international research organisation funding, and some local authority funding. Industry funding and commercial income were most prevalent with 21% of the 'other' sources generated from these sources.

Primary funding source

The primary public funding source was overwhelmingly the research councils (Figure 2.14) at 59% of infrastructures. The reliance on the research councils increased to 66% when considering only those infrastructures most dependent on public funding for their overall costs (i.e. reliant for >70% of establishment costs). This is not surprising given 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 41% of infrastructures record their primary public funder as either Innovate UK, a government department, arms-length public body or devolved funder. The most frequently mentioned government departments as either primary funder or a contributor were Department of Business Energy and Industrial Strategy, Department of Health & Social Care, Department for Digital, Culture, Media and

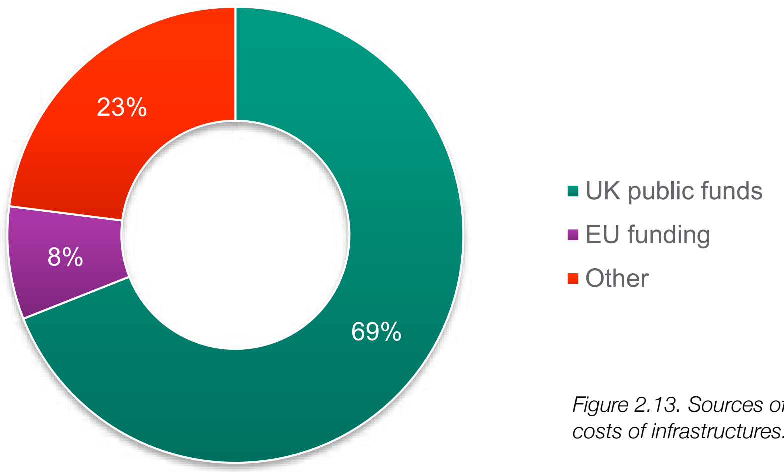


Figure 2.13. Sources of funding for the operational costs of infrastructures.

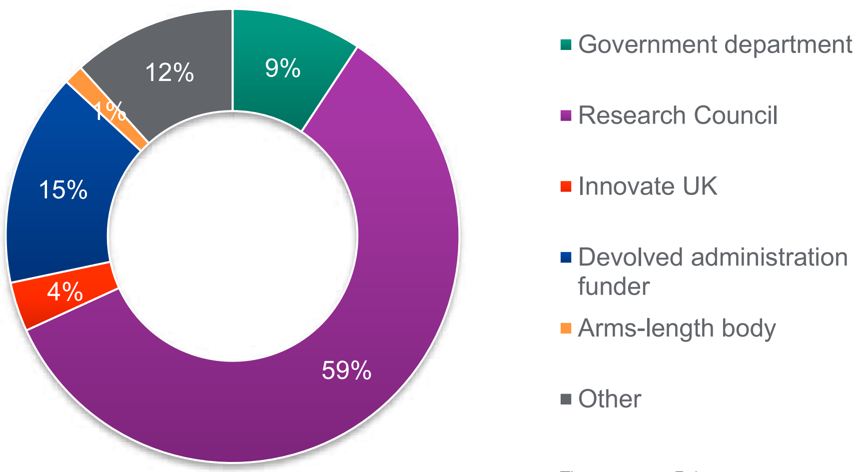


Figure 2.14. Primary source of public funding for infrastructures.

Sport and local sources (Local Enterprise Partnership or Local Authority).

The role of research capital funding provided directly to universities through devolved funders (Scottish Funding Council, Higher Education Funding Council for Wales, Department of Employment and Learning Northern Ireland and Higher Education Funding Council for England now Research England) is complex[13,14]. Some infrastructures report this funding stream as either their primary source of funding or acknowledge it for its contribution. However, some infrastructures did not include research capital funding in their funding sources even though they are hosted within a university. It is likely that devolved funders do provide some underpinning support, 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 is not possible to explore the precise allocation of funds in this detail through this questionnaire.

The primary source of funding did vary across the sectors (Figure 2.15) reflecting the nature of the subjects supported. SSAH reported a higher reliance on devolved funders and other sources, reflecting a greater dependence of that community on university funding. E-infrastructure has a balanced spread across funding sources reflecting the underpinning nature of this infrastructure across disciplines and organisations. Energy has the highest proportion of government departments listed as the primary funder reflecting the various initiatives from different parts of government to support energy policy. Environment has a particular reliance on the research councils.

Links to the wider economy

Innovation can be considered as the application of knowledge or ideas for the development of products, services or processes – whether in business, public services, or non-profit sectors. For this programme, we have extended this definition to infrastructure as *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 infrastructures with the primary aim of collaborating to support innovation, research and innovation campuses and infrastructures where researchers enable innovation from their research.

Overall, 75% of infrastructures reported that they worked directly with businesses to some degree (Figure 2.16). Of the 25% that reported that they didn't work directly with business, 13% were at an early stage of lifecycle (design, development or implementation) before significant business engagement would be expected in most cases.

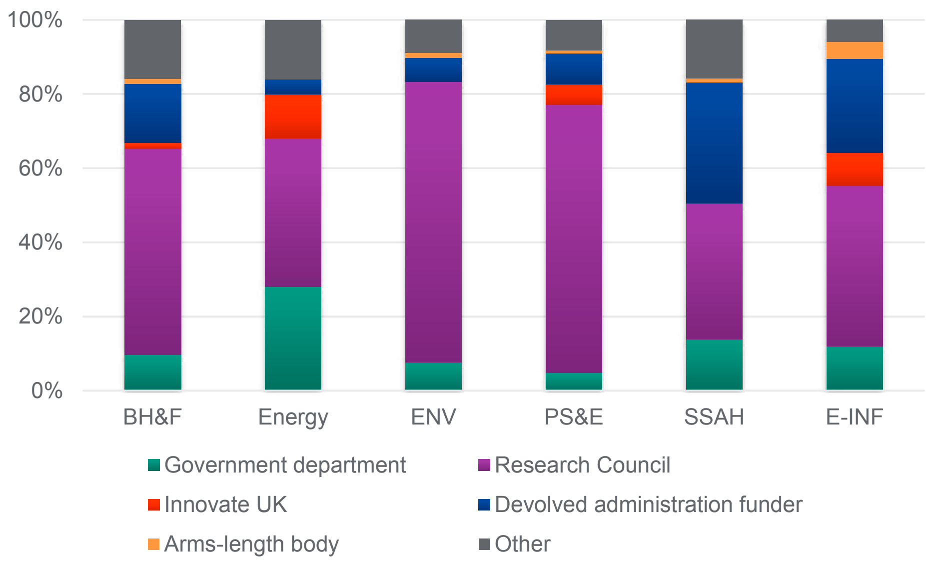


Figure 2.15. Variation in the sources of primary funding for infrastructures across the six sectors.

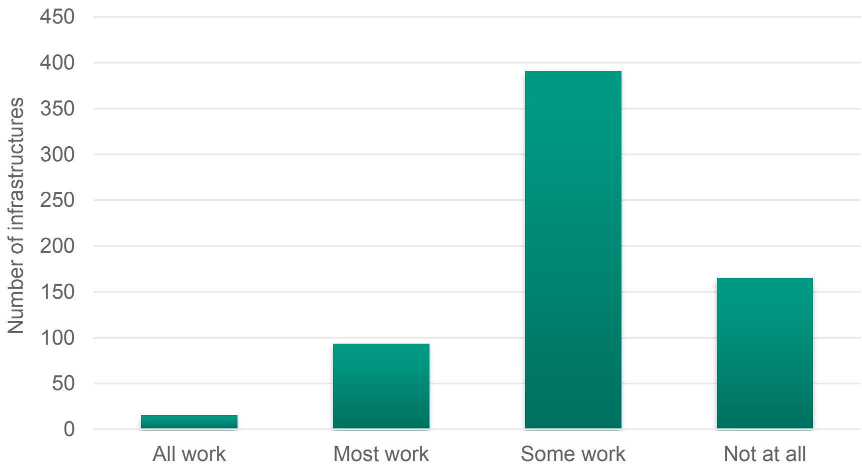


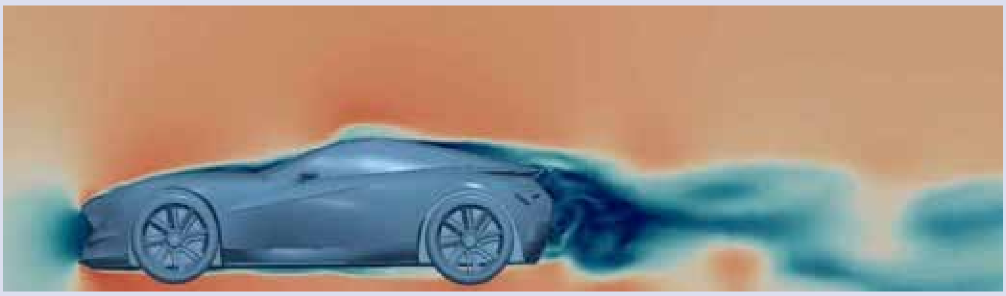
Figure 2.16. The extent to which infrastructures work with businesses, including work that is informed and defined by, but not funded by, business.

The Hartree Centre is transforming UK industry through high performance computing, big data and cognitive technologies (AI)[15]. Developed following significant funding from UK Government, and with strategic partnerships with major industry leaders, the Hartree Centre brings together some of the most advanced systems, technologies and experts in these fields.

It is the only supercomputing centre in the UK with industrial engagement as its primary role. The Hartree Centre was established to allow UK businesses, ranging from large corporate organisations to start-ups and small businesses, to benefit from the specialist expertise and access to supercomputers and other emerging technologies that would normally only be available to academic researchers. The sectors of the economy identified where Hartree is generating impact include: consumer goods (32%), energy (6%), manufacturing (14%), transport (6%), chemicals (7%), ICT (14%) and other sectors (21%).

In the first 4 years of operation the Hartree Centre has achieved:

- 100 projects with commercial companies
- A further 67 projects with other organisations such as the Met Office bringing wider societal impact
- £27.5 million net commercial benefit to its users
- Additional £7.1 million net impact from its operational expenditure
- 130 training courses, totalling 3,760 training days



Credit: UKRI

Virtual Wind Tunnel: An innovative approach to computational fluid dynamics for aerospace and automotive prototyping.

The knowledge and innovation roles of infrastructures make important contributions to the economy. We asked infrastructures to select the economic sectors that they contribute to from a list of 40 economic sector categories based on grouped Standard Industrial Classification divisions[16] (see Methodology for details). Research and engineering and education were the top sectors identified with, followed by health and public policy. Twenty-eight economic sectors were selected by 80 or more infrastructures, and all of the 40 economic sector categories were identified by at least 20 infrastructures each, demonstrating the broad economic and societal impact generated by infrastructures. The average number of economic sectors that infrastructures worked with was seven, although this varied across domain sectors (Figure 2.17). E-infrastructures worked with twice as many economic sectors than other infrastructures, reflecting the cross-cutting nature of this sector.

Table 2.1. The top 20 economic sectors that infrastructures identified with, excluding the option "other" that captured all sectors not listed in the options. Note that infrastructures could select as many economic sectors as were relevant to them. Numbers indicate the number of infrastructures that identified with each.

Economic sector		**Economic sector**	
Research and engineering	407	Manufacturing - chemicals	150
Educational services	317	Manufacturing - electronics	148
Health services	277	Transportation - automotive	139
Public policy	252	Transportation - aeronautical	137
Utilities - energy	213	Manufacturing - food and beverages	130
Agriculture	203	Transportation - other	127
Manufacturing - pharmaceuticals	200	Services - creative industries, recreation	127
Communications and information	186	Construction	112
Manufacturing - instrumentation	185	Manufacturing - transportation	110
Computing (including data & AI) & communications	179	Manufacturing - other	108

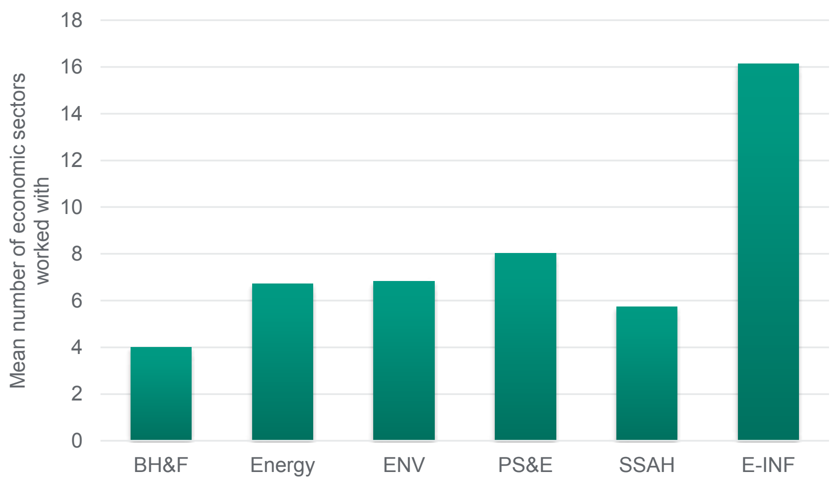


Figure 2.17. The mean number of economic sectors that infrastructures work with according to the primary domain sector they identify with.

There are notable differences in the extent to which infrastructures place themselves on a scale from *discovery research* to *commercialisation* (Figure 2.18). Overall, 41% stated that they were either balanced between both ends or were more commercially focused. The remaining 59% were more discovery focused (Figure 2.18). Energy infrastructures have the greatest focus on the commercialisation end of the spectrum and SSAH have the greatest focus on discovery.

It is possible that different sectors will have interpreted this commercialisation question in different ways. The commercialisation result can be contrasted with the response of infrastructures to whether they directly contribute to shaping public policy or delivering public services. In this case 51% felt that they did and the proportion for each sector are shown in Figure 2.19. SSAH infrastructures have a high likelihood of being involved in shaping public policy (67%), which is unlikely to have been considered as an aspect of commercialisation, but which is their main route to impact.

It is notable that Energy has the highest proportion of infrastructures in terms of commercialisation and policy/public services. This may be a reflection of the sector's significant direct funding by government departments and focus on areas of application that are highly regulated. Other sectors have less focus on commercialisation as they are more directly involved in underpinning research.

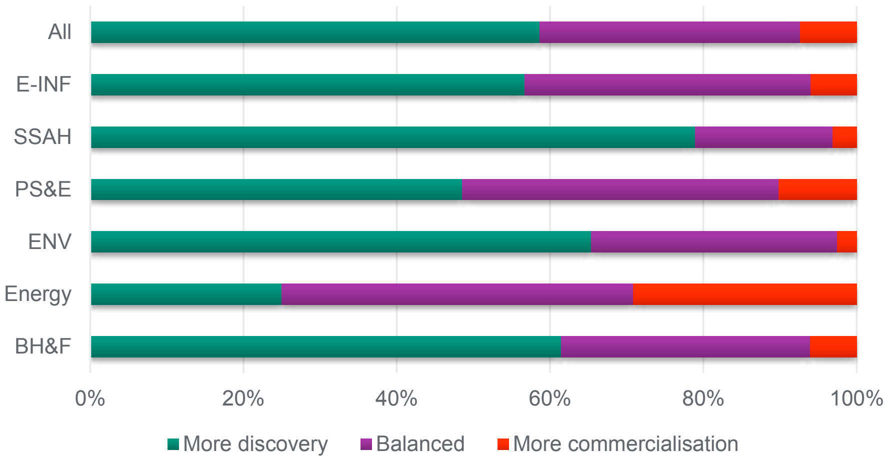


Figure 2.18. Sector differences in their placement on a discovery to commercialisation spectrum.

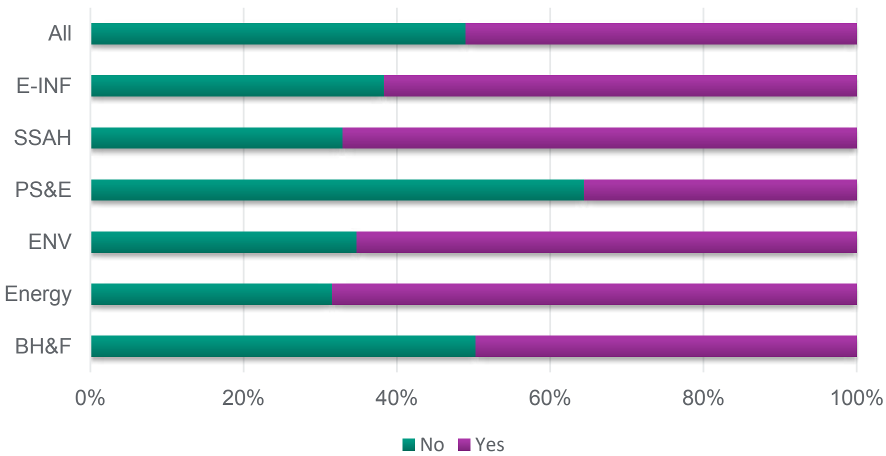


Figure 2.19. The percentage of infrastructures that contribute to shaping public policy or delivering public services.

The Catapult Centres are not-for-profit, independent physical centres that connect businesses – large and small – with the UK's research and academic communities. Each Catapult centre specialises in a different area of technology, but all offer a space with the facilities and expertise to enable businesses and researchers to collaboratively solve key problems and develop new products and services on a commercial scale. They turn commercial ideas into a reality, support businesses to access global growth markets, anchor high value jobs and attract inward investment from globally mobile technology businesses. They are designed to transform the UK's capability for innovation in specific areas and help drive future economic growth. The 2017 Catapult Network Impact Report[17] stated that the network operated facilities worth £850M, delivered 636 academic collaborations, created 2,473 industry collaborations and supported 2,851 SMEs.

Ten Catapults have been established during the lifetime of the programme:

- The Cell and Gene Therapy Catapult – Stevenage & London
- Digital – London (with regional centres)
- Transport Systems – Milton Keynes
- Satellite Applications – Harwell and five regional centres
- Compound Semiconductor Applications – South Wales
- Energy Systems – Birmingham
- Medicines Discovery – Alderley Park
- Offshore Renewable Energy – Glasgow, Blyth & Levenmouth
- High Value Manufacturing
    - Advanced Forming Research Centre AFRC – Strathclyde
    - National Composites Centre NCC – Bristol
    - Centre for Process Innovation CPI – Wilton, Darlington & Sedgefield
    - Advanced Manufacturing Research Centre AMRC & Nuclear AMRC – Rotherham
    - Manufacturing Technology Centre MTC – Ansty
    - WMG – Coventry
- Future Cities

Skills and staff

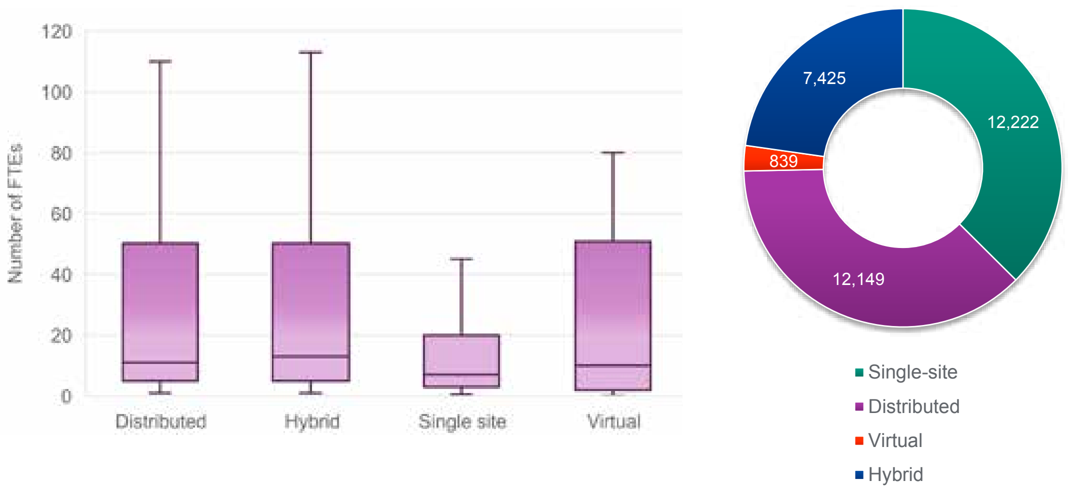
Research and innovation infrastructures of all sizes require staff with highly specialised skills to maximise the potential utility of the infrastructure, from the managers of these infrastructures to the technicians that operate them on a daily basis. Having these skills in place not only realises the day to day function of an infrastructure but also contributes to the innovation of new technologies, 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, nationality, sex, ethnicity (BAME – Black, Asian and minority ethnic backgrounds), staff roles and studentships/ apprenticeships. Where appropriate the staffing of infrastructures has been compared to staffing across UK HEIs according to HESA 2017 data[18] combined for academic and non-academic staff.

Numbers

The general pattern of staff numbers across the sectors mirrors that of the size (in terms of number of infrastructures) of the sectors. Staff numbers were measured as the number of FTEs to control for variation in working patterns. Single-site infrastructures have a smaller average number of staff in each infrastructure compared to virtual and distributed infrastructures (Figure 2.20a), but because single-site infrastructures are more numerous they still employ a similar total number of staff to distributed infrastructures (Figure 2.20b). There is little difference in the average number of staff working at distributed or virtual infrastructures, or those with a mixed model (Figure 2.20a).

The number of FTEs employed by each sector in the UK follows the same pattern as the number of infrastructures in each sector, with PS&E and BH&F employing the largest number of staff (Figure 2.21). The median number of staff working at each infrastructure is also fairly consistent across sectors at 9-12 FTEs, although the range does differ.

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 2.22a). This pattern is partly driven by a relatively small number of very large and often international infrastructures typical of this field, such as the Large Hadron Collider at CERN, the European Southern Observatory and the High Value Manufacturing Catapult. These mega-scale infrastructures are more often in the physical sciences. Of the 33 infrastructures in our dataset with a FTE headcount of 450 or more, almost half are in the PS&E sector (Fig 2.22b).



(a) Average staff (FTE) numbers

(b) total number of staff

Figure 2.20. Employment at different types of infrastructures: (a) the median number and distribution of staff FTEs at infrastructures and (b) the total number of infrastructures employed in each of the types of infrastructure organisation. To interpret the box and whisker plot of (a), the horizontal line through the box represents the median and the box includes the 50% of infrastructures around the median (25th to 75th quartiles). The whiskers represent the range for the top and bottom 25%, excluding outliers.

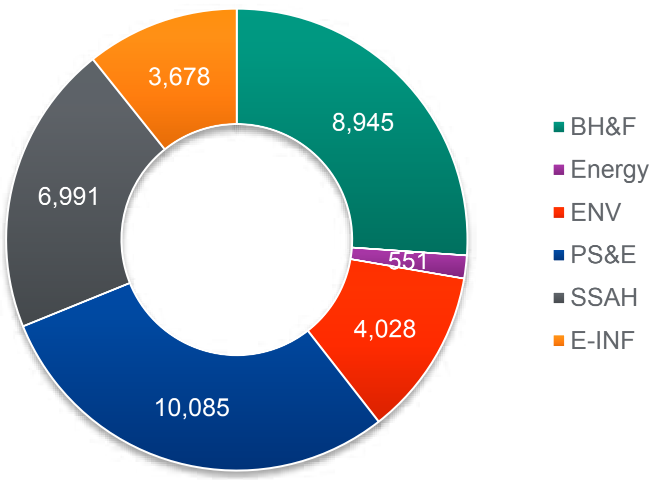
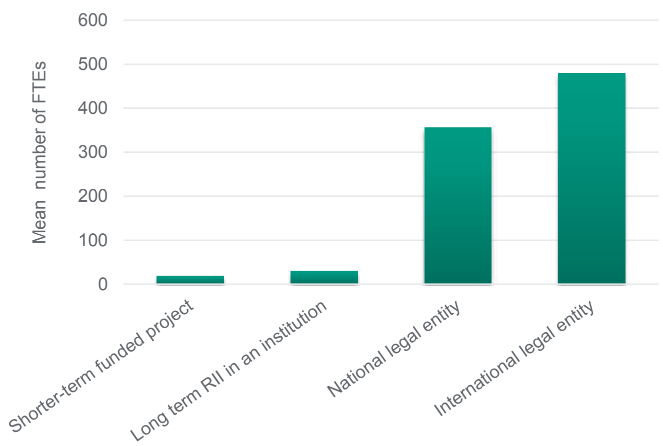


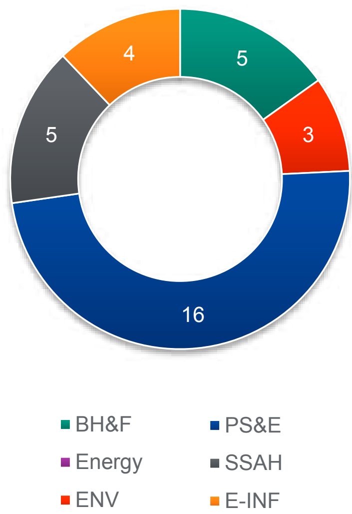
Figure 2.21. Staff numbers (FTEs) employed at infrastructures in each of the six sectors (restricted to infrastructures located in the UK).

Mean Skills and staff by role

Infrastructures require a range of different roles to function that can be broadly categorised as research, technical or other roles (e.g. management, administration etc.) Five of the six sectors have almost three-quarters of their staff performing research and technical roles (Figure 2.23). Social sciences, arts and humanities sector has 56% of staff listed as being in ‘other roles’, which includes large ESFRI infrastructures as well as museums, archives and collections.



(a) Mean staff numbers (FTEs)



(b) Distribution of very large infrastructures (≥450 FTEs)

Figure 2.22. (a) 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. (b) The sectoral distribution of very large infrastructures (with 450 or more FTE's).

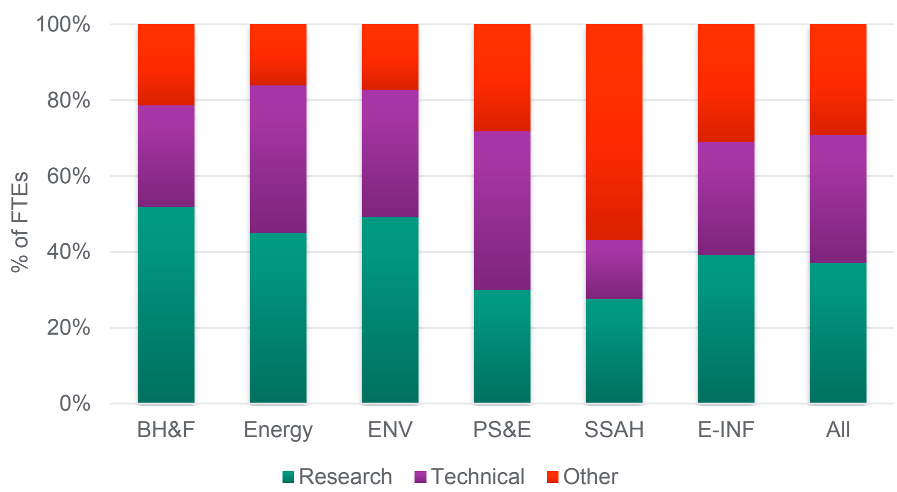


Figure 2.23. Staff roles in infrastructures. On average, 37% of staff employed by infrastructures fill research roles, 34% technical roles and 29% other roles.

Foundries: A fertile training ground

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; the very foundation of modern bioscience research. 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.


Credit: Edinburgh Genome Foundry


Credit: Edinburgh Genome Foundry

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. The UK Centre for Mammalian Synthetic Biology, based at the University of Edinburgh, has started to address this 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 an HND 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.

Diversity

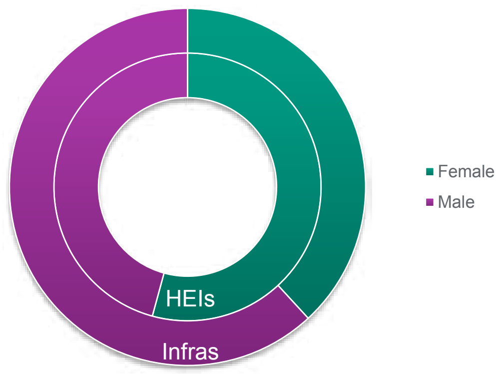
Infrastructures employ proportionally fewer females and a slightly smaller proportion of staff with a BAME ethnicity compared to staff employed by HEIs in the UK (Figure 2.24a and b).

Infrastructures employ more staff from outside of the UK (25%) than the HEI sector as a whole (20%) (Figure 2.25). Sixteen percent of staff from infrastructures come from the EU (excluding the UK), higher than that in HEIs (12%).

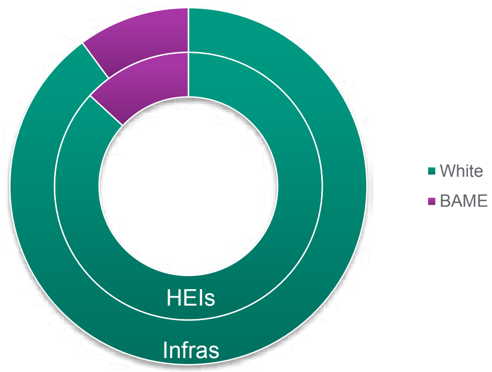
Barriers

The majority of barriers to maximising the benefits of infrastructures were common across all sectors. Figure 2.26 below clusters responses under the main themes discovered.

Unsurprisingly, concern around funding issues was most commonly cited. In addition to the need for sufficient 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’. A further concern was the complexity of the funding sources as some infrastructures were grappling with the recent changes to the landscape and how to react to new funding streams and structures. Uncertainty and potential loss of EU funding sources was also frequently cited.



(a) Sex



(b) Ethnicity

Figure 2.24. The proportion of staff employed at UK infrastructures (outer circle) and HEIs (inner circle) according to (a) sex and (b) ethnicity. Proportionally more staff employed at infrastructures are male compared to staff at HEIs (54% vs 38%). Slightly fewer staff at infrastructures have a BAME (Black, Asian, minority ethnicity) ethnicity compared to staff at HEIs (10% vs 13%) (HESA staff data 2017).

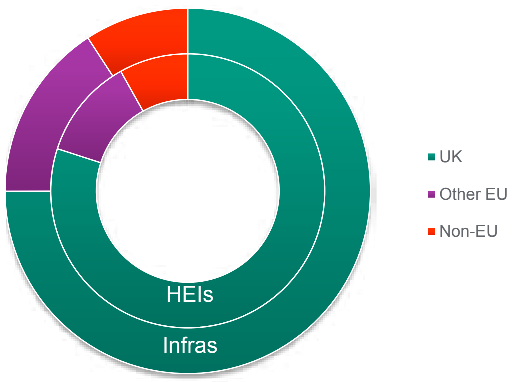


Figure 2.25. The nationality of staff employed at UK infrastructures (outer circle) and HEIs (inner circle).

Shortages of personnel and shortage of key skills, which were often interlinked, were the next cited barriers. Retention of key people, particularly digital/analytical/technical skills (across all sectors) sets was a recurring barrier as were concerns around recruitment and international mobility. Many respondents linked this to the short term nature of funding availability meaning it was only possible to offer short term contracts which are less attractive when more competitive salaries are available in the private sector.

Other barriers that were referenced included: accessing and sharing of data, managing complex partnerships (most commonly in multi-country or multi-funder collaborations), 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, academia or linking to business.

Infrastructures cited broadly similar concerns for future issues, 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 mention 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, other infrastructures and private sector) ability to build the user community and how to increase capacity to engage business users. There was also uncertainty over EU Exit, the evolution of the economy, the impact of new technologies and how the research environment itself will change with a 'lack of strategy' cited 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.

Research and innovation infrastructures are working to mitigate these risks. The common mitigations cited were:

- Diversification of funding streams
- A range of strategies to manage succession problems, increase attractiveness of roles and bring new 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 benefits
- 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 (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 which the infrastructure cannot manage itself such as data access concerns

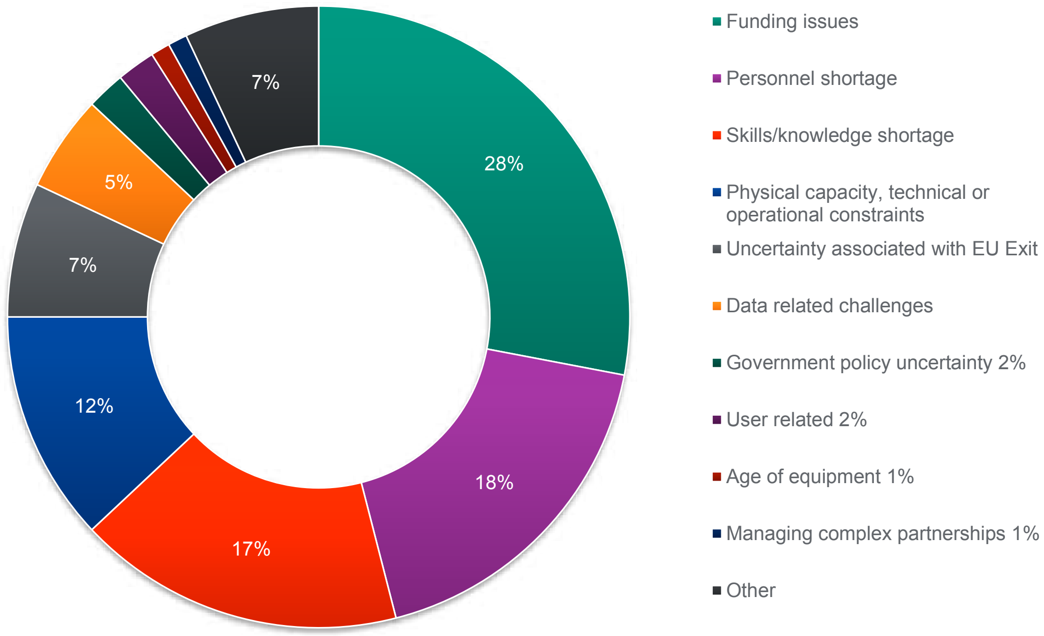
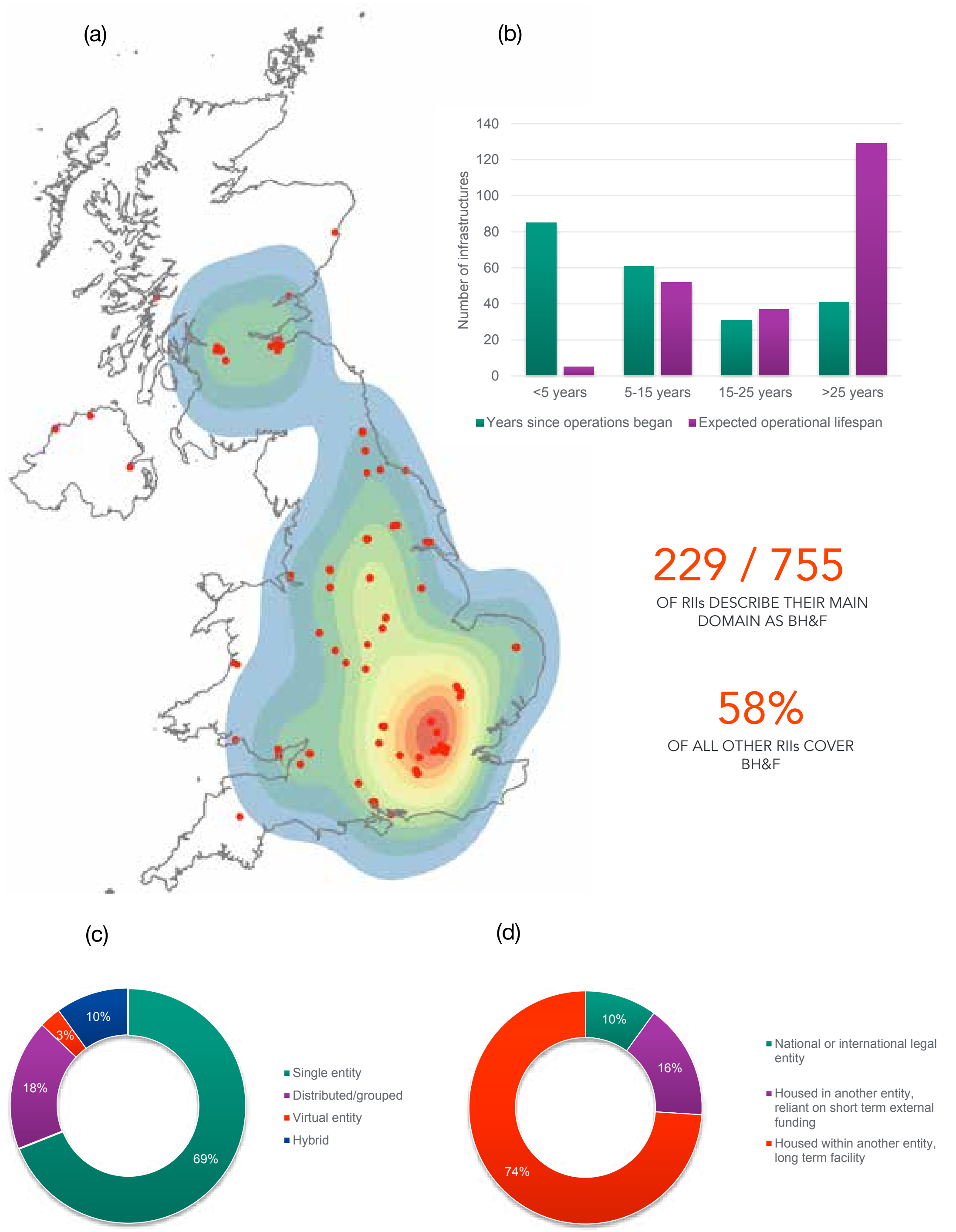


Figure 2.26. The top barriers to maximising output cited by infrastructures.

Chapter 3:
Biological sciences, health and food sector



229 / 755

OF RIIs DESCRIBE THEIR MAIN DOMAIN AS BH&F

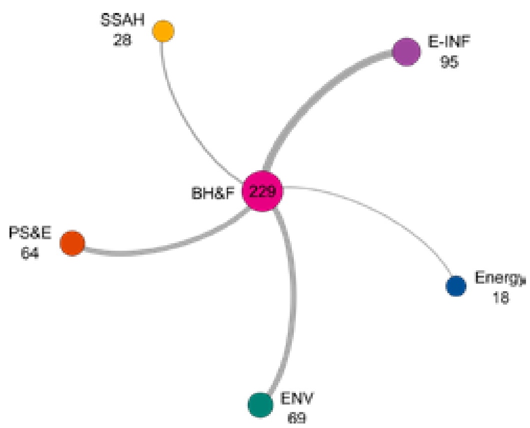
58%

OF ALL OTHER RIIs COVER BH&F

Figure 3.1. (a) The geographical location of infrastructures in the BH&F sector across the UK. Red dots can indicate individual infrastructures or clusters at one location, red colours indicate highest densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/distributed entities or virtual (digital). (d) The distribution of infrastructures according to their legal structure.

Overview

Research and innovation in the biological sciences, health and food (BH&F) sector uses an array of world class infrastructures and capabilities to understand the complexities of form, function and the interactions within and between organisms, and to translate these discoveries for societal and economic benefit. The biological sciences explore complex fundamental scientific questions by utilising the huge amount of data produced 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 and advances in technology have increased, 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 working together to solve the present and future problems to which our society is or will be exposed.



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

Figure 3.2[i]. The overlap (co-occurrence) between the BH&F sector and the other sectors that have relevance to BH&F.

Figure 3.2 highlights the strength of overlap between infrastructures in the BH&F sector (central circle) and the other sectors. The figure highlights that there are strong interdependencies across E-infrastructure, PS&E and Enviromental sectors.

The analysis of the BH&F sector landscape will help to highlight opportunities to support the delivery of world class infrastructure to ensure the UK continues to create innovative solutions in the future. Within the UK much of the public-sector research is covered by the remits of the Biotechnology and Biological Sciences Research Council (BBSRC) and the Medical Research Council (MRC). In addition, the BH&F sector has strong links to:

- Clinical infrastructures supported by the National Institute for Health Research[19] funded through the Department of Health and Social Care
- Biomedical research charities[20]
- Industrial/commercial partners who support innovation

The UK is well connected with European infrastructures and is a partner in 8 out of 13 Biological and Medical Sciences Research Infrastructures supported by the European Strategy Forum for Research Infrastructures (ESFRI) programme[12].

Current Landscape[ii]

Our understanding of the BH&F sector has been derived from a number of sources including the responses to the UKRI landscape questionnaire, previous reports[21,22], discussions with a specially convened expert working group and community workshops. The data presented relate to the outputs from the landscape questionnaire and the supporting narrative is used to convey additional messages that have come from all sources.

Infrastructures in BH&F include biological tissue banks and other collections of biological samples, integrated arrays of

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[i] Acknowledgement: Sci2 Team. (2009). Science of Science (Sci2) Tool. Indiana University and SciTech Strategies, http://sci2.cns.iu.edu. Individual scaling applied.

[ii] The data presented within the BH&F chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which 20 identify BH&F as their primary sector.

small research facilities, high-capacity/throughput technology, high-cost cutting-edge analytical infrastructure, high fidelity imaging technology, networks of computing infrastructures, databases and research cohorts of volunteers. Figure 3.3 depicts the breadth and diversity of BH&F sub-disciplines that were supported by infrastructures across the UK, from crop science and agriculture through to target validation for drug discovery. The 38 sub-disciplines (represented by coloured dots) are based on the categories used by the Research councils' grants submission system.

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

- **Knowledge-based resources**, such as UK Biobank[23] which is a national and international health resource that provides researchers with access to clinical and biomedical information on 500,000 people to improve the prevention, diagnosis and treatment of serious and life threatening human diseases
- **Distributed**, major multi-user capabilities such as ELIXIR, the European life-sciences Infrastructure for biological Information, comprising a Hub, and nodes from 21 partner countries. The UK is host to the ELIXIR Hub which is co-located with the Wellcome Sanger Institute and EMBL-EBI at the Wellcome Genome Campus, near Cambridge, UK. The UK node currently consists of 15 organisations with the Earlham Institute as the lead institution
- **Networks** of cutting edge precision equipment, such as those established through the Clinical Research Capabilities and Technology Initiative[24] to be in close proximity to clinical investigation and care facilities in order to advance clinical research

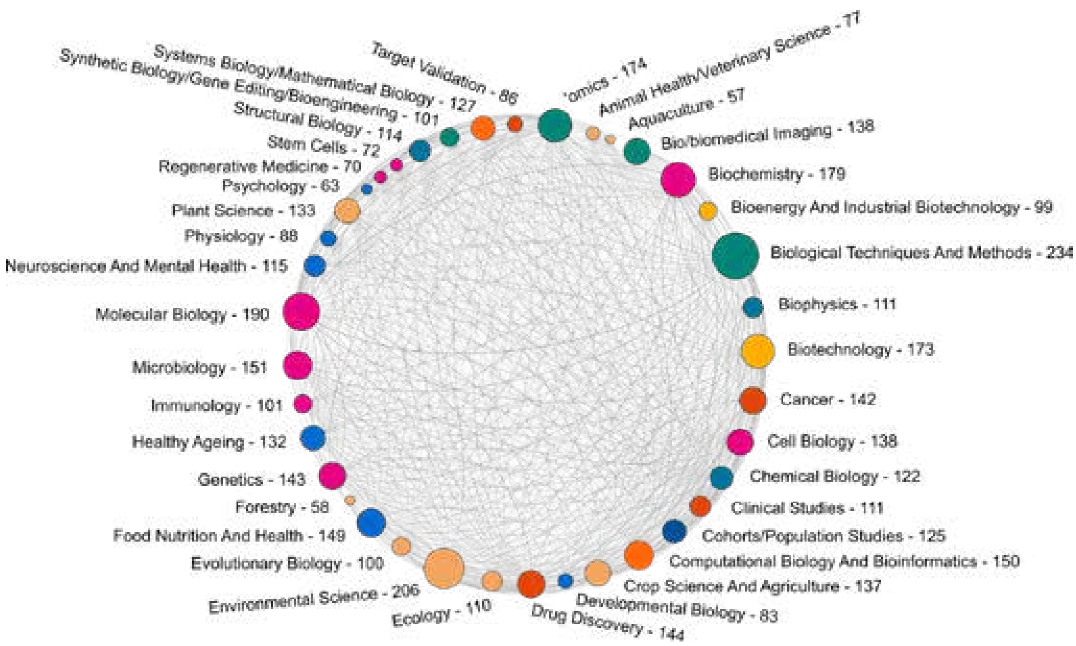


Figure 3.3[iii]. BH&F sector sub-disciplines and overlaps/linkages. Nodes represent the breath of disciplines supported by the BH&F sector. The size of the node relates to the number of infrastructures that selected each BH&F sub-discipline and the web of connecting lines reflects the extent of co-occurrence (overlap) between sub-disciplines. Similar coloured nodes represent more closely-related sub-disciplines. This indicates both the number of infrastructures associating with each discipline and the overall level of interconnectedness between them.

[iii] Acknowledgement: Sci2 Team. (2009). Science of Science (Sci2) Tool. Indiana University and SciTech Strategies, http://sci2.cns.iu.edu. Individual scaling applied.

- **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[25], the national and international reference laboratories for viral diseases at the Pirbright Institute, the National Avian Research Facility (NARF) whose aim is to improve the productivity, health and welfare of poultry, based at the Roslin Institute, and the North Wyke Farm Platform to study grassland livestock systems, which is a worldwide unique national and global research facility that is linked to real-world farming.

The infrastructures that engaged with the questionnaires came largely from UKRI funded/part-funded projects and included few clinical research infrastructures funded through other means, e.g. the UK Department of Health and Social Care. Whilst the UK has a rich clinical infrastructure e.g. a network of biomedical research centres, bio-resources and bio-sample facilities, these are under-represented in the data presented.

Of the 755 infrastructures with a regional, national or international scope, 229 reported their main domain as the BH&F sector. In addition, 58% of the other respondents also highlighted that their infrastructures had relevant links to the BH&F sector (Fig 3.1). This high percentage of linkage highlights the integration of diverse disciplines and the engagement and involvement of scientists from the physical, engineering, computational, mathematical, and the social sciences in tackling the research challenges across the life sciences community.

Many UK infrastructures are funded through competitive processes. They are awarded based on research strengths so tend to be located close to the academic user base. The contour map of the UK illustrates the spread of infrastructures in the BH&F sector (Figure 3.1a). The red dots across the map indicate that BH&F infrastructures are located across the four nations of the UK. The contours on the map indicate that there are two areas of higher infrastructure density, one in Scotland, and a larger one in the south of England. Approximately 16% of BH&F infrastructures are located in Scotland, and about 45% of the reported infrastructures are located in the South and East of England (including London). The remaining 37% in the UK are distributed broadly and located close to areas of scientific excellence, with three BH&F infrastructures being located outside the UK.

The link to universities was highlighted in the questionnaire with 72% of infrastructures being housed within another legal entity (e.g. university or bespoke research institute) and a further 17% being short-term projects, again usually co-located within universities and other institutes. This tallies with the geographically dispersed nature of the infrastructures in this sector and also has implications for longer-term sustainability.

Research and innovation infrastructures are a long-term investment

The long-term investment required to support research infrastructures in the BH&F sector is highlighted (Figure 3.1b). Almost 20% of BH&F infrastructures have been operational for over 25 years with 10% having a 40-year or more operational existence. Figure 3.1b suggests a large increase in new infrastructures in recent years, but the data do not illustrate the complex picture regarding the lifecycle of infrastructures, e.g. the level of turnover of existing infrastructures, the repurposing/re-development of long-standing facilities, or the new infrastructures that arise to support and maximise previous investments.

Almost three-quarters of infrastructures indicated that looking towards the future, they expect that their infrastructures would have an operational lifespan of ≥15 years, 57% of which expect this to be ≥25 years. The difficulty in securing long-term operational funding may be linked to 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. Fewer than 12% of respondents could confidently plan beyond a 6-year horizon with over half being able to plan less than three years in advance. This will have implications on both strategic planning and the overall efficiencies that could be achieved with greater certainty of funding. Almost one third of infrastructures supporting the BH&F sector are distributed (comprised of multi-site facilities) or virtual (e.g. access digitally). With these the highest cost is often not in the initial construction, but in the long-term recurring costs required for running, maintaining and replacing/updating facilities.

Research and Innovation Infrastructures at Research Institutes

Credit: Rothamsted Research

Rothamsted Research was founded in 1843 and is the longest running agricultural research station in the world. It is home to the oldest continuous agronomic (field) experiments in the world (the Long-Term Experiments) that started between 1843 and 1856 and are still running. 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.

The National Virology Centre at the Pirbright Institute (formerly the Institute of Animal Health). The institute has been in existence for over 100 years, first 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, which is at the forefront of international virus research. The site has been recently redeveloped to incorporate a state-of-the-art high containment (SAPO 4) laboratory home to the BBSRC National Virology Centre.

Credit: UKRI

Population cohort data

Some of the very old infrastructures are long-standing data collections e.g. the 1936 Lothian Birth Cohort. The UK houses many unique, historical population data sets and to maximise the utility of these investments new capabilities have evolved to support their interpretation. For example, to support the interpretation of complex health datasets, a distributed health informatics research institute, The Farr Institute, was established in 2012 and a new successor institute, Health Data Research UK, was 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.

Characteristics and uniqueness of infrastructures in the BH&F sector

The future spread of infrastructures may alter as the shift from scientific research being largely delivered by individual research groups that focus on very specific questions, to more holistic approaches (discovery-driven research) that rely on large distributed team(s) with common access to expensive infrastructure, becomes more evident. This approach is highlighted by the large number of ESFRI infrastructures (pan-European collaborations) that the UK contributes to.

There is some indication of change as evidenced by the mix of legal structures that were reported across this sector; six infrastructures had charitable status and four were limited companies. Ten per cent of infrastructures were established as national or international legal entities, supporting the creation of large-scale capabilities to enable discovery science across the UK and beyond. An example of this is Instruct-ERIC[26]. The UK leads and hosts the headquarters of this distributed pan-European infrastructure, which supports structural biologists across Europe to access to highly specified

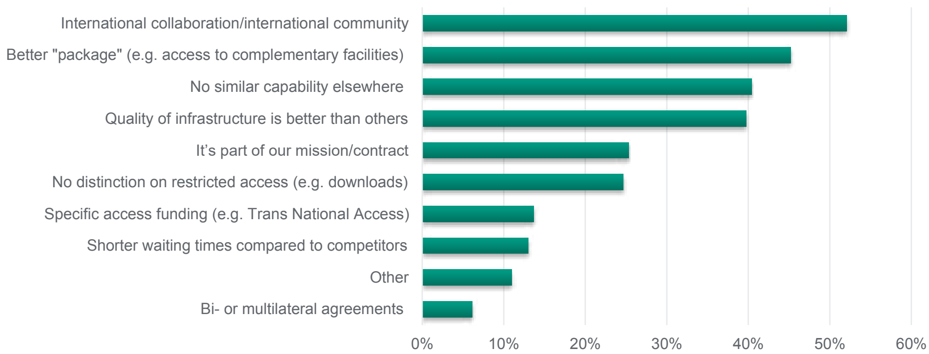


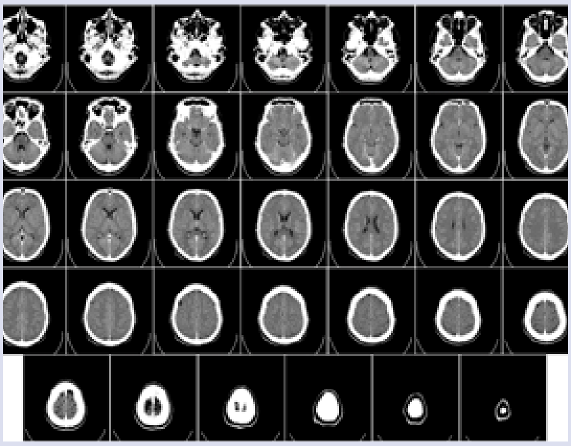
Figure 3.4. Reasons given by researchers and innovators for why they are attracted to infrastructures in the BH&F sector.

equipment e.g. direct electron detectors in EM, synchrotron sources and detectors, XFELs, ultra-high field NMR, super-resolution cryo-light microscopy and computational capabilities.

Collaboration is almost ubiquitous in the BH&F sector with 93% of infrastructures reporting that they collaborate with other organisations. Of these, 78% report that they collaborate both nationally and internationally. Overseas users are attracted to UK BH&F infrastructures for a variety of reasons (Figure 3.4), including the need to collaborate, uniqueness of infrastructures and excellence and colocation with complementary facilities.

UK Biobank – infrastructure for population studies and precision medicine

UK Biobank[27] is the largest European biobank available to date and a flagship infrastructure for the UK. Launched in 2006 and funded equally between the MRC and the Wellcome Trust, it is a vast resource containing biomedical data from half a million individuals in the UK who have been followed for 10 years. It has set a new standard for implementing population studies at this scale, more than a decade ahead of the NIH launching the US 'All of Us'[28] study which aims to recruit at least 1 million US citizens.



There is significant industry interest in UK Biobank; the basic-level genotype data on all 500,000 participants is linked to disease incidence (2018 release) and is already being mined by industry for new target genes. A consortium of companies and charities are now funding deep sequencing of participants, contributing close to £200m as part of the UK Government's Industrial Strategy Challenge Fund. Hundreds of research teams apply to access the UK Biobank, with studies already yielding valuable results and over 500 scientific publications to date.

Two studies from 2018, combining UK Biobank data (including genetic data using blood samples) with other cohorts, demonstrate the impact of this vital infrastructure resource.

In a pioneering study[29] that combined 10,000 UK Biobank Magnetic Resonance brain images with genetic data from all 500,000 participants, scientists found a genetic link for some fundamental processes that are involved in how we think, act and function. The results will provide an impetus to new research for degenerative and psychiatric disorders and ultimately improve treatments.

In another study[30], researchers identified more than 500 genes that play a role in blood pressure. High blood pressure is a highly heritable and modifiable risk factor for cardiovascular disease. These findings could contribute to an early life precision medicine strategy for cardiovascular disease prevention, allowing doctors to recommend lifestyle changes for those at high risk, preventing thousands of heart attacks and strokes.

Links to e-infrastructure

‘Big Data’ was once the purview of astronomers and high-energy physicists. However, the advent of new high-resolution imaging modalities and the increasing use of high-throughput and automated approaches in genomics has led to ever increasing collections of complex biological data that requires an agile e-infrastructure environment to support them.

E-infrastructure underpins over three-quarters of BH&F infrastructures, with 75% of these using e-infrastructure and data as a tool and the remainder has it as its primary research discipline.

Most (83%) of BH&F infrastructures consider that e-infrastructure and data would increase in importance for their infrastructure over the next five to ten years. This highlights that the research community is grappling with the huge volume of data arising from genomics, epigenomics, transcriptomics, proteomics and metabolomics.

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

At the international scale the European Bioinformatics Institute (EBI) based near Cambridge is part of the European Molecular Biology Laboratory (EMBL) 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 27 million web requests per day. The EBI 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.

Links to the wider economy

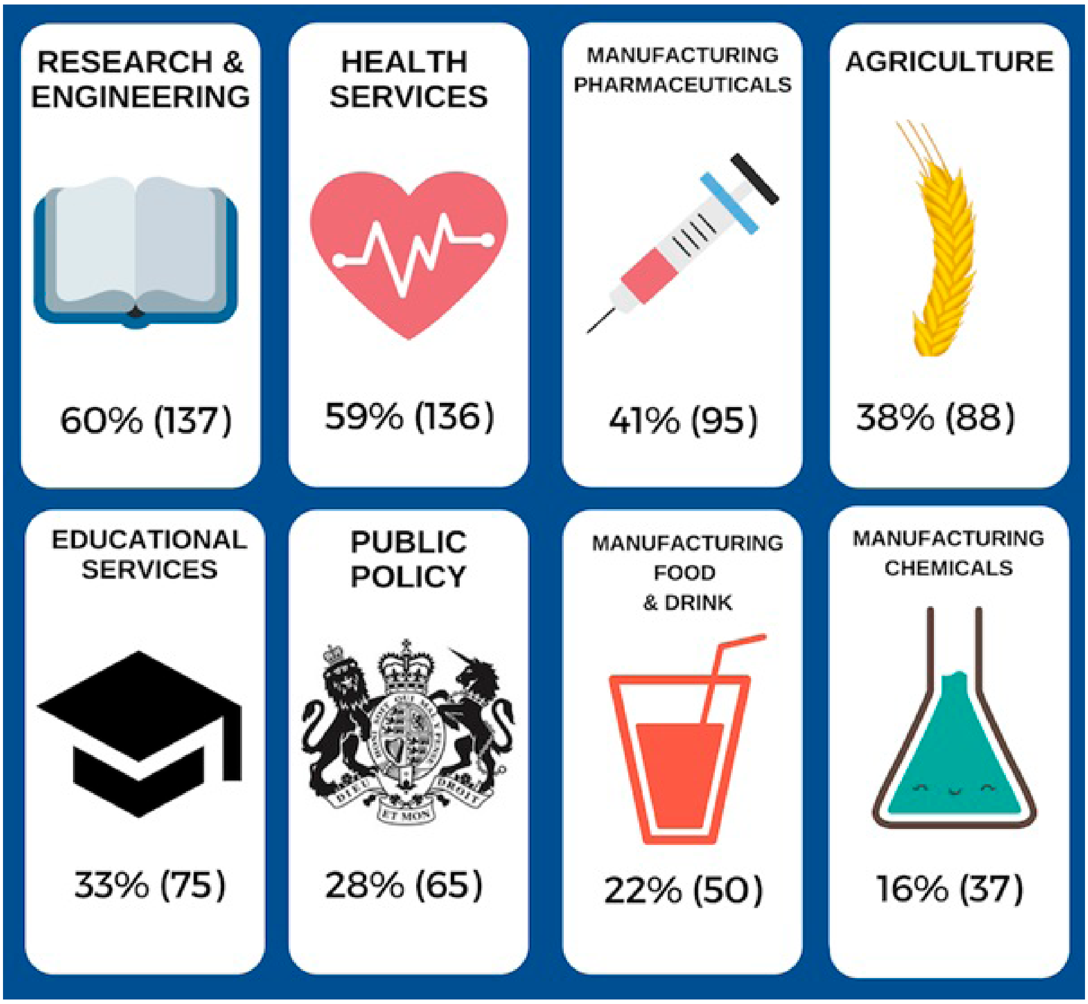
Discovery and challenge-led research are supported by the ability to access world-class infrastructures. The innovation and translation of research findings has impacts on other sectors of the economy. The top eight sectors of the economy that benefit from access either directly to research infrastructures or the scientific outputs they support are shown in Table 3.1. The top sectors supported are the health services, agriculture, the pharmaceutical industry, and the food industry. There are also strong links to public policy.

Accelerating drug discovery

Two MRC-led partnerships with global pharmaceutical companies, UCB and AstraZeneca, will help accelerate potential therapies from laboratory bench to patient bedside by promoting open innovation. The partnerships will support collaboration between researchers and industry scientists and access to industry infrastructure to advance discovery research.

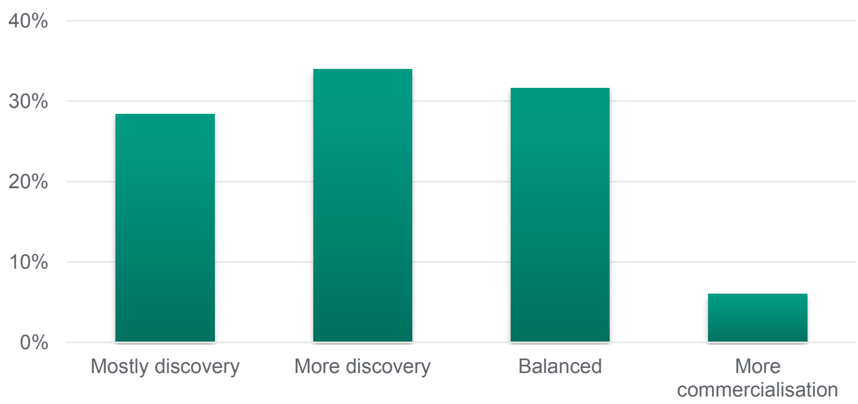
The MRC/AstraZeneca Cambridge Centre for Lead Discovery is jointly staffed by industry and academic researchers allowing unprecedented access to high-throughput screening via AstraZeneca’s drug discovery robotics platform (NiCoLA-B) and a high-quality, chemically-diverse compound library of over two million compounds. Developments in robotics and technology mean that facilities can now screen more than 300,000 compounds per day, helping to make the process of drug discovery smarter, faster and cheaper.

Table 3.1. Top eight economic sectors that BH&F infrastructures work with.



The primary purpose of most research within the BH&F sector is towards 'discovery/ blue skies' science (59%) (Figure 3.5). Only 6% of infrastructures output is primarily towards commercialisation although 31% conduct '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.

Infrastructures can be developed under various business models. Over a third of BH&F infrastructures were set up through partnership between public and private funding sources. These consortia and partnerships add additional value by bringing broad stakeholder experiences (charities, business, other public sector bodies) into the management and strategic planning of infrastructures. The majority of infrastructures in the BH&F sector have engagement with industry as 73% of infrastructures reported doing 'some', 'most' or 'all' of their work with UK businesses. Only 27% reported that they did not directly work with UK businesses.



38%
Work with non-academic public sector (>5% activity)

73%
Claim at least some work is informed by businesses

Figure 3.5. The spread of BH&F infrastructures on a discovery to commercialisation spectrum.

Norwich Research Park (NRP) is a multidisciplinary research and business community which aims to deliver solutions to the global challenges of healthy ageing, food and energy security, sustainability and environmental change. It comprises a cluster of world-leading research institutions with 3,000 scientists and over 80 businesses, enabled by over £150 milllion investment in research and innovation infrastructure since 2011.

NRP is a partnership between the John Innes Centre, the Earlham and Quadram Institutes, the Sainsbury Laboratory, the University of East Anglia, and the Norfolk and Norwich University Hospitals NHS Foundation Trust. The NRP research partners have pooled their infrastructures and provided a single portal for academics and businesses access to their complex facilities. These infrastructures include microscopy/imaging, genomics/ bioinformatics, flow cytometry, proteomics/metabolomics, chemical and structural studies, environmental analysis, growth facilities and scientific collections.

Translational activity on the NRP is growing, facilitated by the infrastructure and wider support for industry/academic interactions, early-stage translation and business growth.


Credit: Quadram Institute

Flexible space is available for business innovation and translation, including the Accelerator Office and laboratory space, the Centrum innovation hub, UEA Enterprise Centre and the Innovation Centre. Leaf Expression Systems® is a translational facility for the research, development and manufacture of high value products from plants, using technology and knowledge based on world leading research created at the John Innes Centre.

Chapter 4: Physical sciences and engineering sector

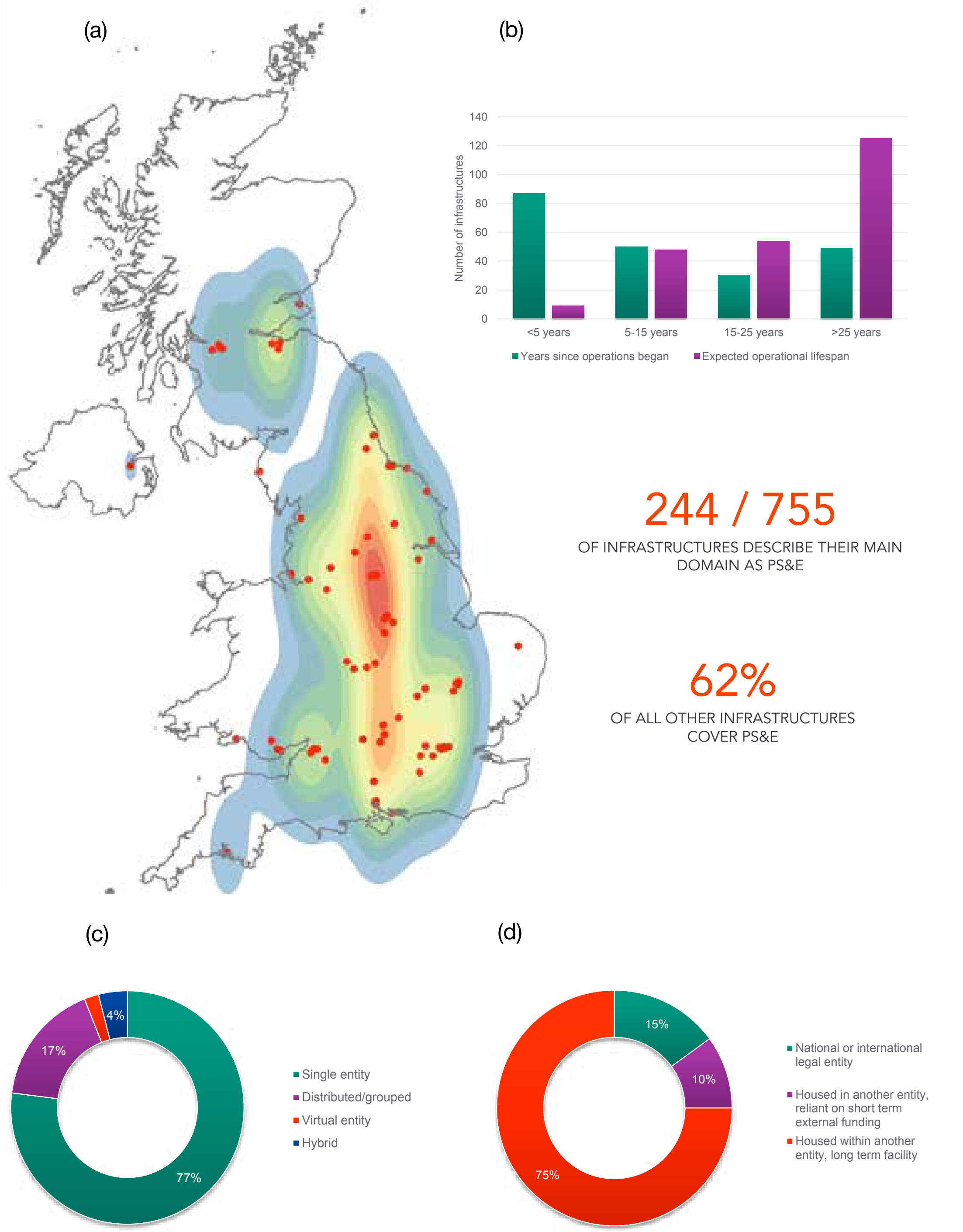


Figure 4.1. (a) The geographical location of infrastructures in the PS&E sector across the UK. Red dots can indicate individual infrastructures or clusters at one location, red colours indicate highest densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/ distributed entities or virtual (digital). (d) The distribution of infrastructures according to their legal structure.

Overview

The Physical Sciences & Engineering (PS&E) research and innovation spectrum reaches all branches of physics, chemistry and mathematics to materials, information and computing technology, quantum technologies, healthcare technologies, engineering and manufacturing.

The infrastructures within PS&E are naturally broad in their nature including specialised large-scale equipment, facilities, institutions and observatories. Infrastructures represent capabilities ranging from lasers and accelerators to mass spectrometry, Nuclear Magnetic Resonance (NMR) and imaging. Facilities can also host multiple infrastructures such as suites of telescopes (e.g. European Southern Observatory [ESO]) or detectors (e.g. European Organisation for Nuclear Research [CERN]) and multiple capabilities.

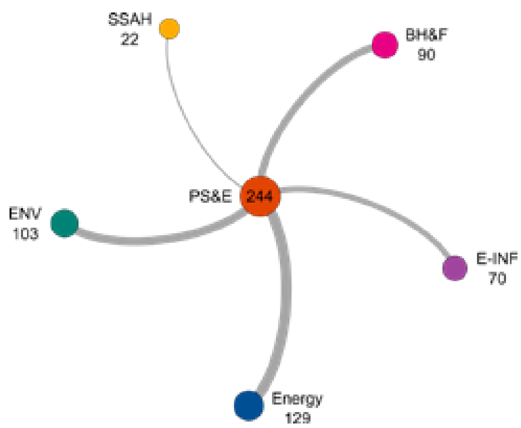
Research in this sector increasingly relies on sophisticated experiments at a range of bespoke national and international facilities, often at the leading edge of what is technically possible. Due to the scale and costs of such facilities many infrastructures can only be realised through international collaborations and long-term strategic planning, for example, infrastructures to facilitate our understanding of the origin and nature of all matter and the development of the Universe and our place within it.

Alongside data from the questionnaires we have held consultations and workshops and sought guidance from existing advisory structures within UKRI to develop this initial picture of the PS&E landscape. Whilst a large number of infrastructures in PS&E did engage through the questionnaire, we are aware that the space sector was not well represented, which should be considered when interpreting the data and results in this chapter.

Current landscape[iv]

A high proportion (32%) of respondents to the UKRI questionnaire named PS&E as their primary domain (Figure 4.1). The PS&E infrastructures also support other science from across all other sectors. For example, 52% of infrastructures in the PS&E sector are also relevant to BH&F. Conversely, many infrastructures in other primary sectors also support PS&E (62%). Figure 4.2 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, Environmental and Energy sectors.

PS&E has a high number of infrastructures with an expected lifespan of over 25 years (Figure 4.1b). This may be a reflection on the size, complexity and physical nature of the infrastructures typical of this sector. There are a high number of infrastructures established in the last 5 years, and up to 50% of them will have a life expectancy of over 25 years. A large proportion of the PS&E infrastructures (77%) responding to the questionnaire are also single-site, focused capabilities, with 17% distributed and only 6% have a virtual or a hybrid/mixed model (Figure 4.1c).



The PS&E sector is placed centrally 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 4.2[v]. The overlap (co-occurrence) between the PS&E sector and the other sectors that have relevance to PS&E.

[iv] The data presented within the PS&E chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which 12 identified PS&E as their primary sector.

[v] Acknowledgement: Sci2 Team. (2009). Science of Science (Sci2) Tool. Indiana University and SciTech Strategies, http://sci2.cns.iu.edu. Individual scaling applied.

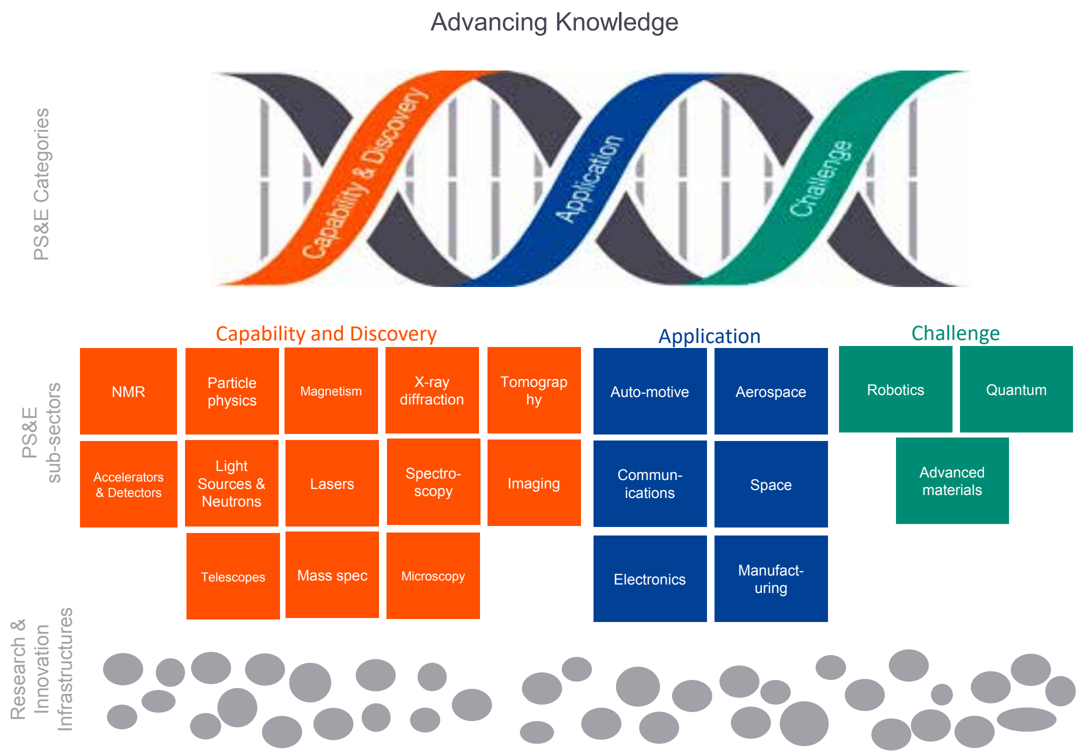


Figure 4.3. The building blocks of the PS&E sector.

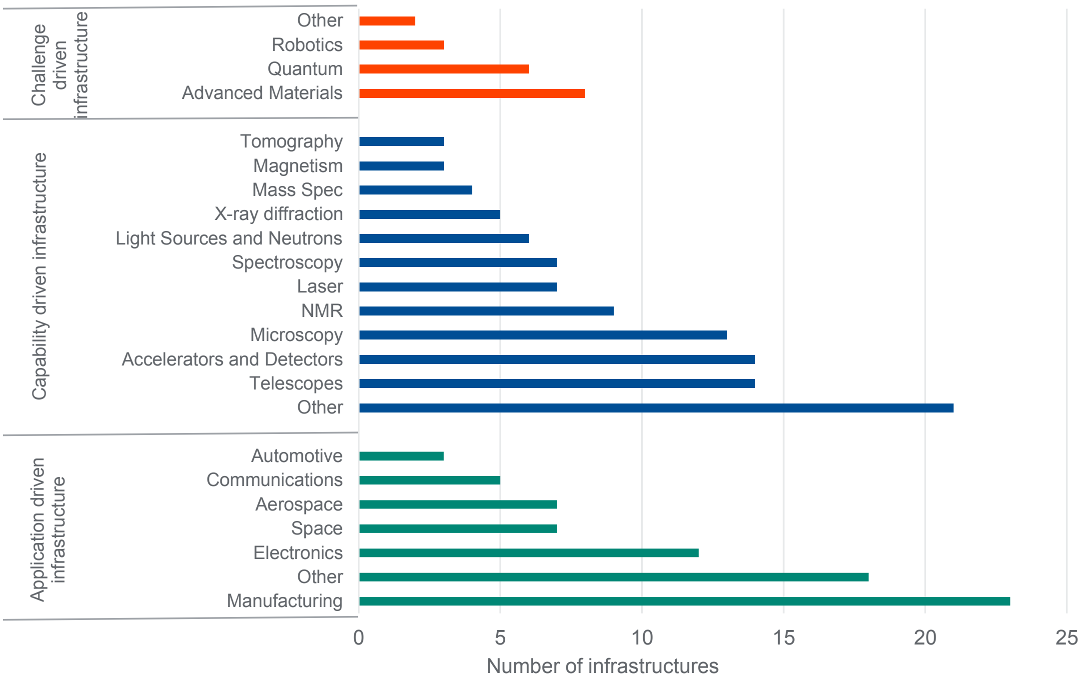


Figure 4.4. The distribution of the PS&E infrastructures across three categories and multiple sub-sectors.

In many cases the different infrastructures provide complementary expertise to each other and to answer complex, interdisciplinary problems a combination of approaches making use of infrastructures from across the different classifications is required, hence the importance of the interconnectivity. The category with the largest number of infrastructures is the capability driven infrastructure category (Figure 4.4). This category also contains the greatest number of large sub-sectors (e.g. those with more than 10 infrastructures per sub-sector). The high numbers of microscopy, NMR, accelerator and detector infrastructures within these sub-sectors reflects the broad and high demand of these types of facilities. This analysis also highlights areas where we are aware there has been a low response from publicly funded infrastructures, such as the space sector.

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. For example:

- National Wind Tunnel Facility (NWTF)
- 5G test beds
- Advanced fabrication and materials growth facilities
- High Value Manufacturing Catapult
- Space Test Facility (RAL)

Credit: National Epitaxy Facility

The National Epitaxy Facility is helping the UK stay at the forefront of the electronics sector. It provides universities and commercial customers with world-class semiconductor materials, and with advice in the field of semiconductor epitaxy – the growth of crystal layers on layers of other materials. The facility is delivered by the University of Sheffield in partnership with the University of Cambridge and University College London. It is making a key contribution to the development of quantum cascade lasers, for example, which have the potential to contribute to leading-edge sensor technologies in a range of environments.

Capability driven infrastructure: these infrastructures provide 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. These 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. For example:

- Integrated analysis and materials characterisation suites
- National scale electron microscopy suites
- European Spallation Source (ESS)
- European Southern Observatory (ESO)

Credit: The University of Manchester

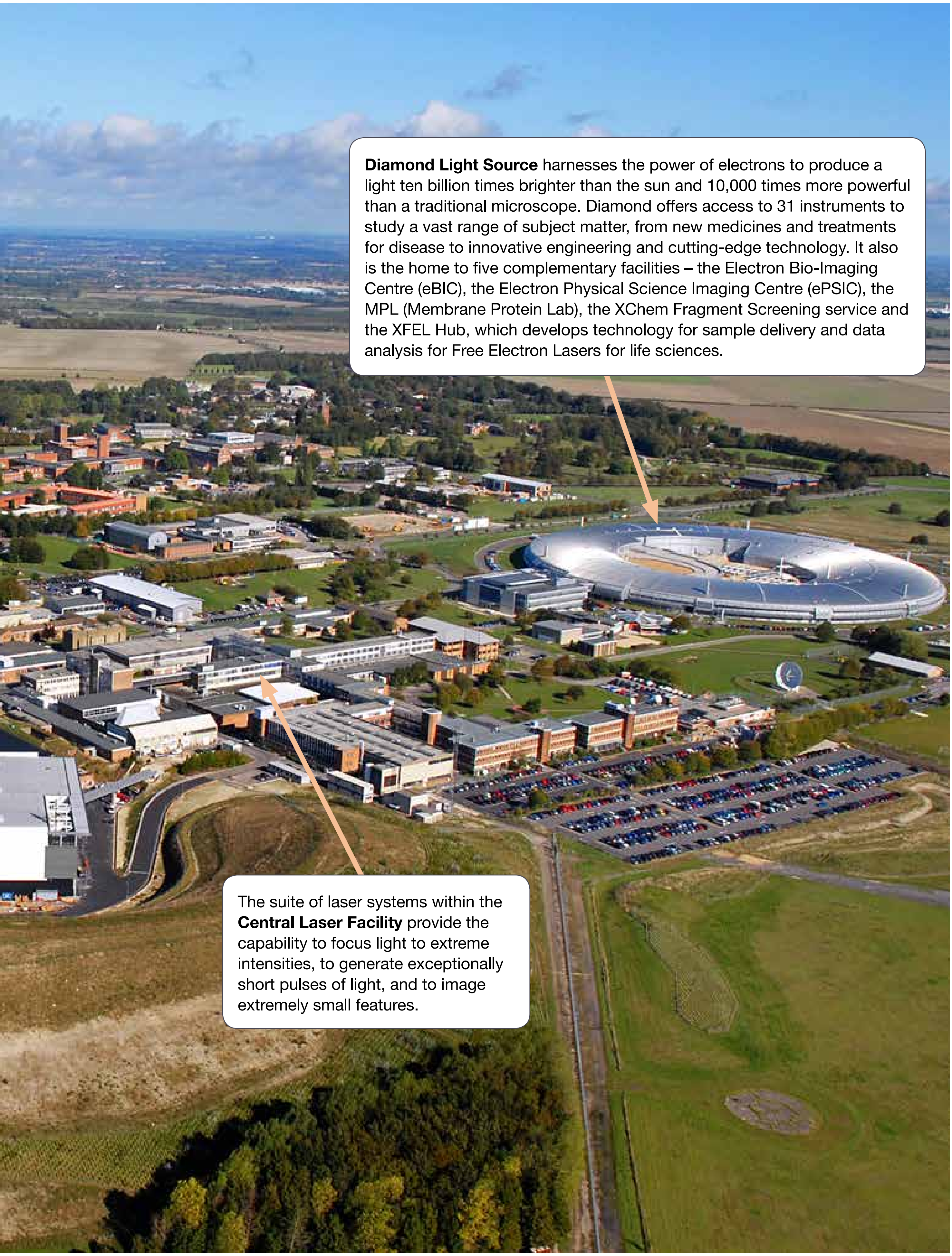
EPSRC National Electron Paramagnetic Resonance (EPR) Facility and Service. EPR spectroscopy is a powerful method for studying all kinds of paramagnetic materials (those containing unpaired electrons). This facility hosted at the University of Manchester handles test samples in the form of crystals, powders, solutions and glasses. It is used to serve researchers in biological molecules and systems, chemistry and materials research as well as a wide variety of industry applications, such as the automotive sector.

Large Facilities at Harwell

The Large Facilities provide national and international access to world-class infrastructure in lasers, synchrotrons, neutrons and muons for universities and industry. The variety of instruments and facilities they contain enables cutting-edge research in many different fields, with applications in areas as diverse as clean energy and the environment, drug design, advanced engineering and electronics.

Based at the Harwell Science and Innovation Campus in Oxfordshire, the Large Facilities contribute to, and benefit from, the campus's thriving community of research facilities, organisations and businesses. This includes Research Complex at Harwell (RCaH) which acts as the gateway to the Large Facilities. It provides multidisciplinary laboratories that allow researchers in the physical sciences, life sciences and laser research to work alongside each other, encouraging collaboration and the sharing of ideas.

ISIS Neutron and Muon Source is the UK national facility for neutron and muon science, helping scientists obtain unique insights into the properties of materials on the atomic scale. It currently has over 30 instruments, covering techniques such as neutron diffraction and spectroscopy, small angle neutron scattering and muon spectroscopy.


Diamond Light Source harnesses the power of electrons to produce a light ten billion times brighter than the sun and 10,000 times more powerful than a traditional microscope. Diamond offers access to 31 instruments to study a vast range of subject matter, from new medicines and treatments for disease to innovative engineering and cutting-edge technology. It also is the home to five complementary facilities – the Electron Bio-Imaging Centre (eBIC), the Electron Physical Science Imaging Centre (ePSIC), the MPL (Membrane Protein Lab), the XChem Fragment Screening service and the XFEL Hub, which develops technology for sample delivery and data analysis for Free Electron Lasers for life sciences.
The suite of laser systems within the **Central Laser Facility** provide the capability to focus light to extreme intensities, to generate exceptionally short pulses of light, and to image extremely small features.

Credit: UKRI

Challenge driven infrastructure: these infrastructures tend to be part of wider initiatives targeted towards addressing major scientific, technical, innovation, societal or policy challenges as part of wider programmes. They often build on outstanding, existing capability, which has been developed over many years through capability driven investments. For example:

Credit: ICI

- Graphene Engineering Innovation Centre
- Sir Henry Royce Institute
- UK National Quantum Technologies Hub
- National Robotarium

The Rosalind Franklin Institute (RFI) is a new national institute dedicated to bringing about transformative changes in life science through interdisciplinary research and technology development. RFI will focus exclusively on problems where physical science technology can enable significant changes in our abilities to answer biological problems with applications in industry. There will be a focus on five themes: structural biology, biological mass spectrometry, next generation chemistry for medicine, imaging with sound and light, and correlated imaging.

Links to the wider economy

PS&E infrastructures are hugely important to the manufacturing sector with six of the top eight economic sectors that PS&E infrastructures contribute to falling within the various types of manufacturing (e.g. chemicals, pharmaceuticals, transportation and electrical) (Table 4.1). The other non-research economic sector falling in the top eight was the utilities. There is also a clear indication that PS&E infrastructures support a diversity of economic sectors because every one of the 40 economic sector choices was selected by at least one PS&E infrastructure, with infrastructures selecting on average nine economic sectors that they each contribute to.

Close links with industry are reflected by the fact that 87% of PS&E infrastructures perform some work that is directly informed by businesses (Figure 4.5). After the energy sector this is the highest proportion of business engagement of all the sectors indicating the close relationship between academia and industry within PS&E. This is also reflected in that 41% of infrastructures consider themselves to be 'balanced' in terms of their position on a discovery research to commercialisation scale.

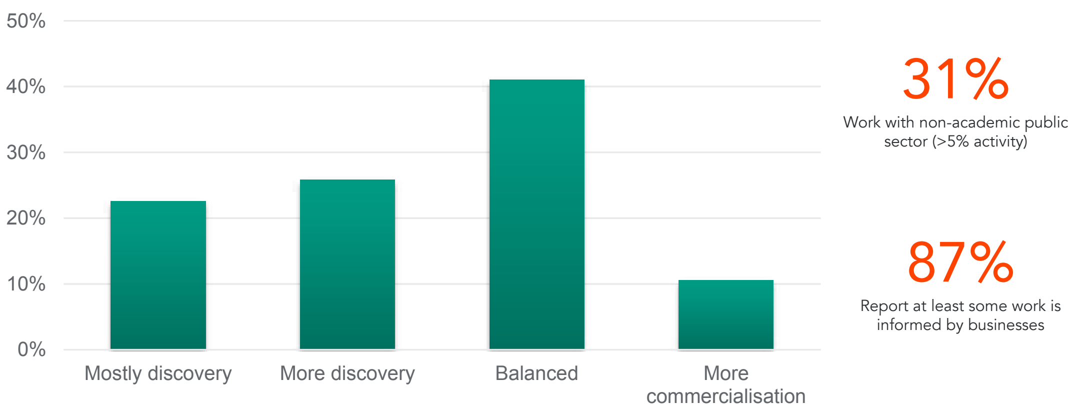
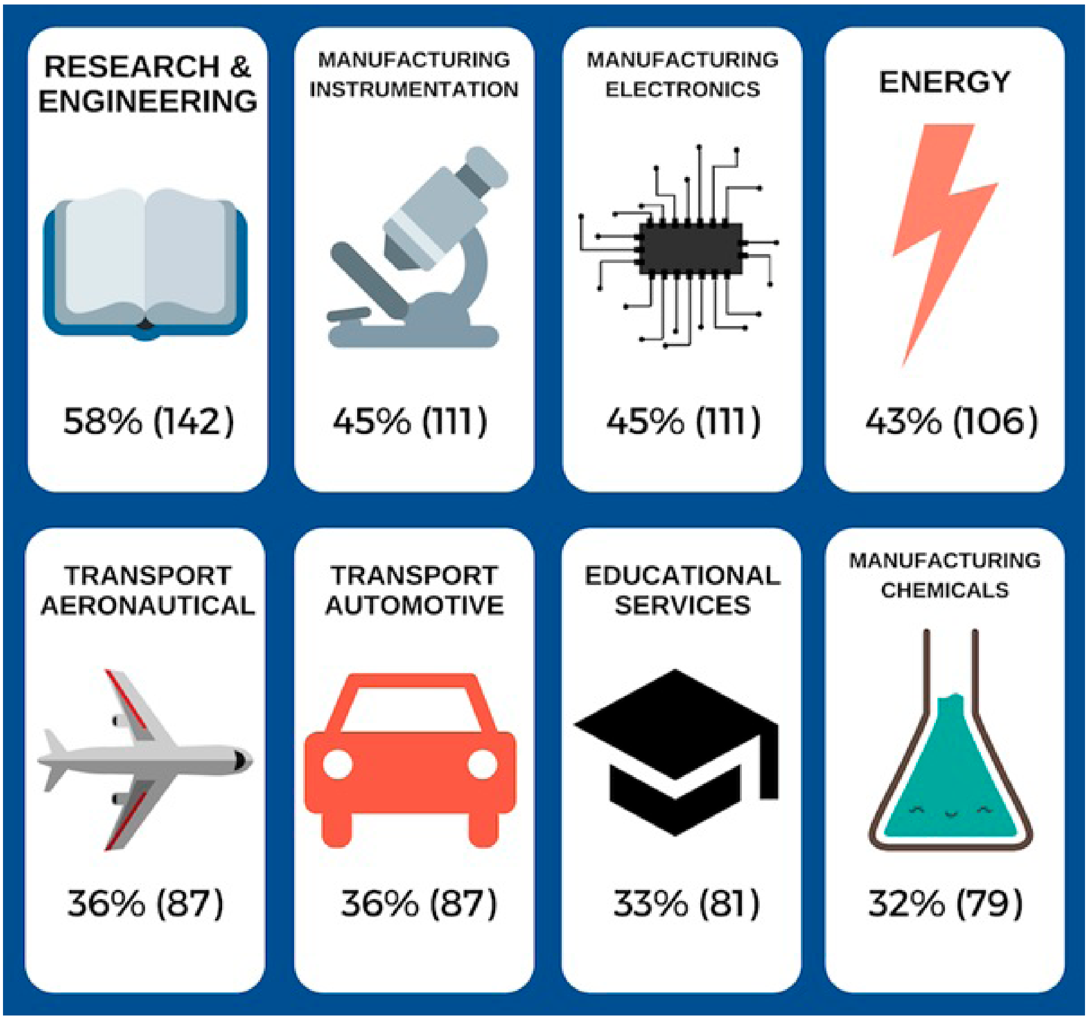


Figure 4.5. The spread of PS&E infrastructures on a discovery to commercialisation spectrum.

Table 4.1. Top eight economic sectors that PS&E infrastructures work with.



E-infrastructure and data

Since the digital revolution the needs of the PS&E sector for data and computationally intensive research have driven the advancement of digital infrastructure, such as the development of the world wide web for information sharing at CERN. The PS&E sector has examples of infrastructures developed as primary e-infrastructure facilities. For example DiRAC is a data intensive and high-performance computing infrastructure for modelling and GridPP is a high-throughput computing infrastructure that primarily supports the experiments of the Large Hadron Collider. Many other PS&E infrastructures whose primary purpose is not data or computing also have significant e-infrastructure requirements. These capabilities are often embed within their facilities e.g. at the European Synchrotron Radiation Facility (ESRF) or the European Southern Observatory (ESO).

The quantity of data and complexity of experiments within the PS&E sector requires both advanced computational modelling and data science expertise. The Ada Lovelace Centre is a new approach that concentrates scientific computing resources and skills alongside the Harwell-based infrastructures. This has the potential to generate a step change in productivity, accelerating the translation of experimental data into research outputs.

E-infrastructure is the primary function or an important tool of 67% of PS&E infrastructures. With infrastructures generating ever greater volumes of data, the reliance on e-infrastructure is expected to increase over time. seventy-three per cent of PS&E infrastructures envisaging e-infrastructure and data to become more relevant to their infrastructures in the next five to ten years. Planning e-infrastructure requirements therefore becomes an important consideration throughout the life-time of an infrastructure.

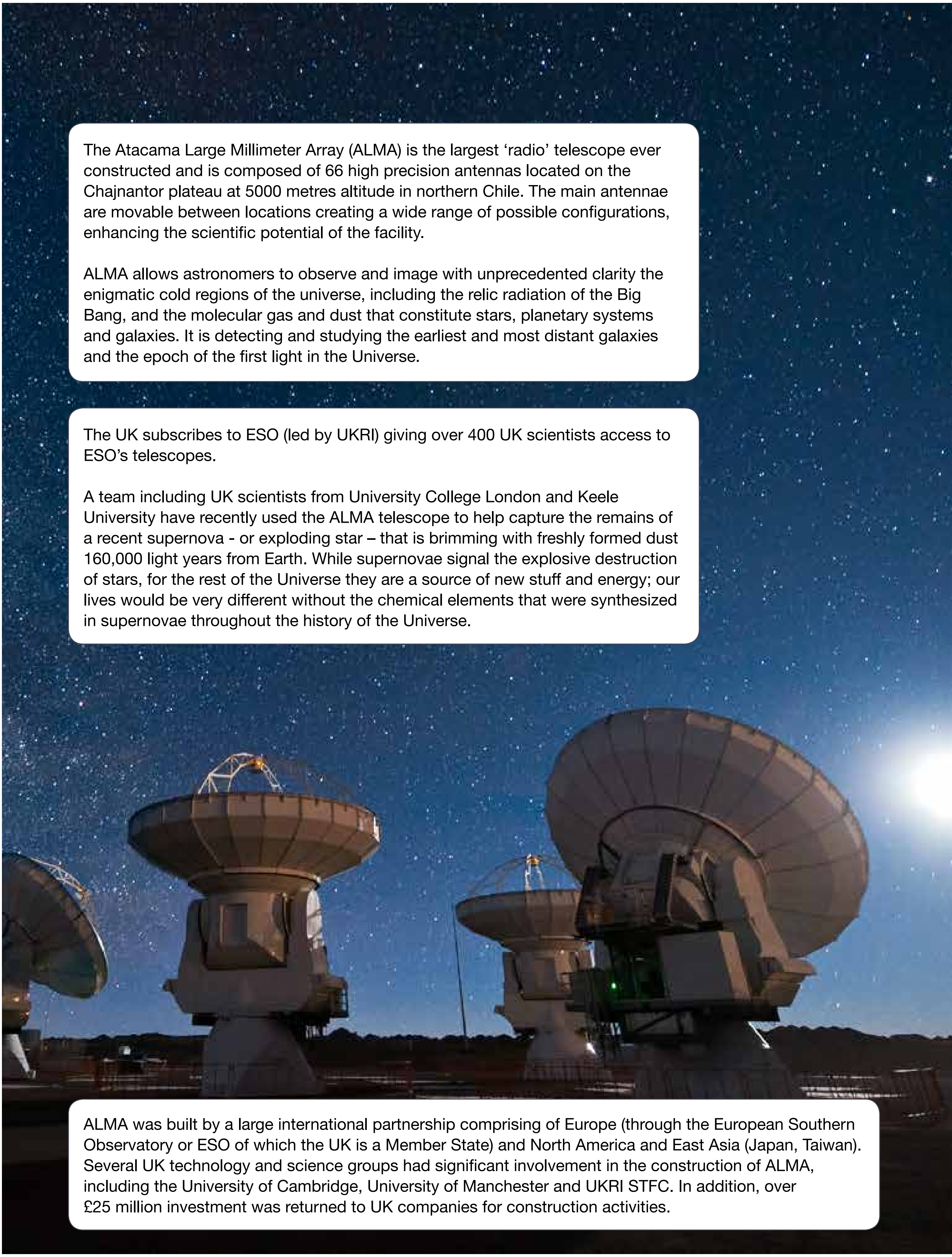
UK Collaboratorium for Research on Infrastructure & Cities (UKCRIC)
UKCRIC is an infrastructure composed of a portfolio of facilities with a mission to underpin the renewal, sustainment and improvement of national infrastructure and cities in the UK and elsewhere. UKCRIC provides leadership and support for the development and growth of a coherent, world-class, UK-based national infrastructure research community. By engaging with government, city and commercial policy makers, investors, citizens and academia, it is a joint venture that drives innovation and value creation in the exploitation of services provided by national infrastructure.

UKCRIC supports a step-change in the nation's approach to infrastructure investment through three key strands of activity.

Test and Experimental Facilities. A set of interlinked national facilities for research on the basic science, technology and engineering that underpins the economic infrastructure sectors and delivers innovative solutions meeting international, national and city needs.

Urban Observatories. A network of 'urban laboratories' for rapid trialling of solutions at scale and gathering/curating large volumes of diverse data about current and proposed infrastructure. This approach will allow policies, regulation, systems and capital investments to be made on the basis of evidence, analysis and innovation.

Modelling and Simulation. An environment to enable 'what if' experiments to be carried out in a high performance computing environment on possible large-scale solutions at national, regional and city level. This will allow the de-risking of proposed large scale investments, give insights into possible futures, and highlight new mechanisms for value capture and benefit realisation.



ESO/Jose Francisco Salgado

The Atacama Large Millimeter Array (ALMA) is the largest 'radio' telescope ever constructed and is composed of 66 high precision antennas located on the Chajnantor plateau at 5000 metres altitude in northern Chile. The main antennae are movable between locations creating a wide range of possible configurations, enhancing the scientific potential of the facility.

ALMA allows astronomers to observe and image with unprecedented clarity the enigmatic cold regions of the universe, including the relic radiation of the Big Bang, and the molecular gas and dust that constitute stars, planetary systems and galaxies. It is detecting and studying the earliest and most distant galaxies and the epoch of the first light in the Universe.

The UK subscribes to ESO (led by UKRI) giving over 400 UK scientists access to ESO's telescopes.

A team including UK scientists from University College London and Keele University have recently used the ALMA telescope to help capture the remains of a recent supernova - or exploding star – that is brimming with freshly formed dust 160,000 light years from Earth. While supernovae signal the explosive destruction of stars, for the rest of the Universe they are a source of new stuff and energy; our lives would be very different without the chemical elements that were synthesized in supernovae throughout the history of the Universe.

ALMA was built by a large international partnership comprising of Europe (through the European Southern Observatory or ESO of which the UK is a Member State) and North America and East Asia (Japan, Taiwan). Several UK technology and science groups had significant involvement in the construction of ALMA, including the University of Cambridge, University of Manchester and UKRI STFC. In addition, over £25 million investment was returned to UK companies for construction activities.

Chapter 5: Social sciences, arts and humanities sector

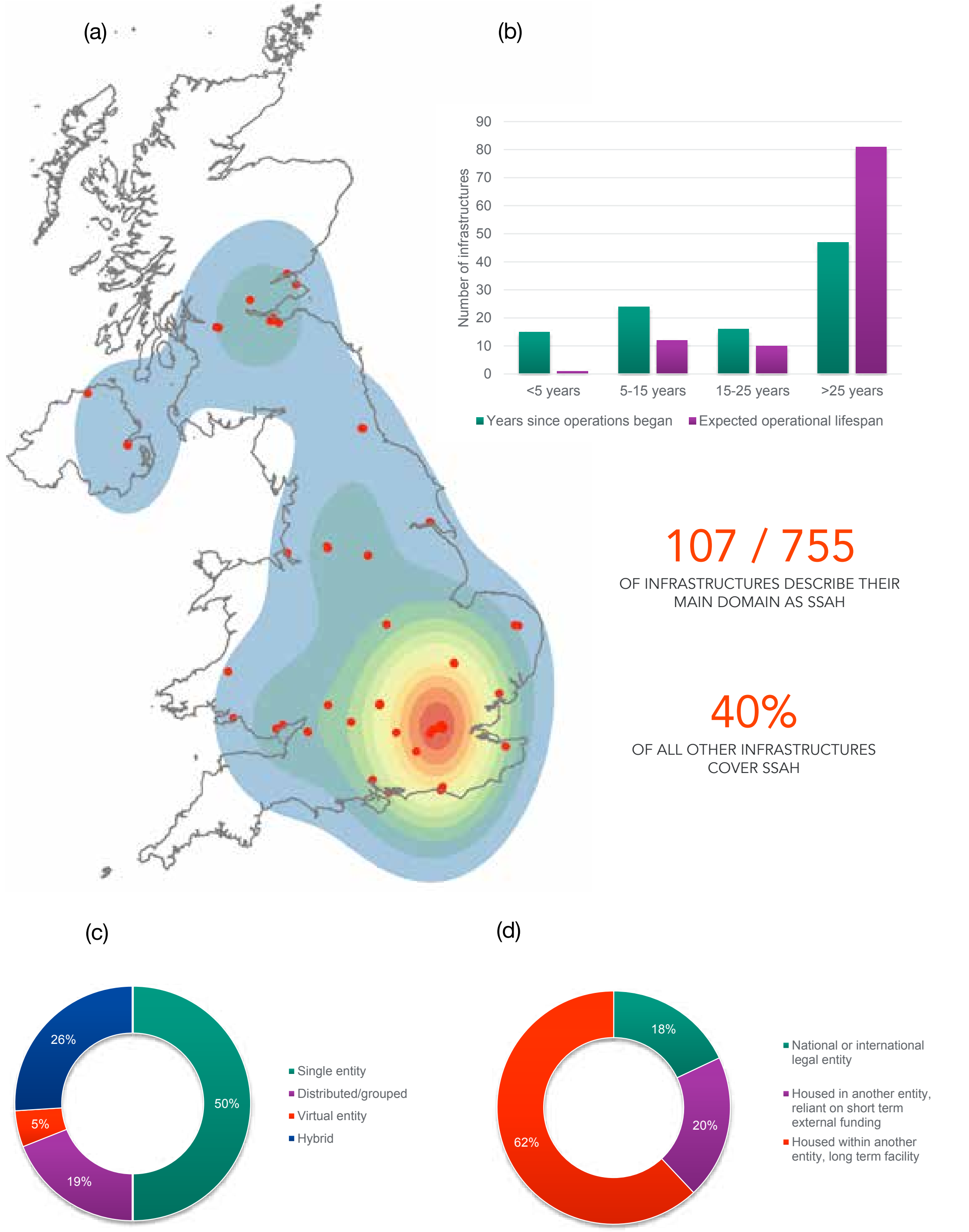


Figure 5.1. (a) The geographical location of infrastructures in the SSAH sector across the UK. Red dots can indicate individual infrastructures or clusters at one location, red colours indicate highest densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/ distributed entities or virtual (digital). (d) The distribution of infrastructures according to their legal structure.

Overview

The Social Sciences, Arts and Humanities (SSAH) research and innovation infrastructure sector is a large and diverse sector focussing on infrastructures that serve the social sciences, including economics, and the arts and humanities, including the heritage sector. The infrastructures in this sector consist of a large group that are concerned with allowing access to research objects. These objects can include physical research objects (in collections, libraries or archives), the digitised versions of these objects, or data derived from research or collected directly from source. These infrastructures sit along a continuum, from infrastructures that are intended to serve the whole of the research base (museums, galleries, collections), through infrastructures that collate data or knowledge (e.g. from administrative, government or business sources) to infrastructures that are intended to support particular disciplines (for example those covering history or religion or financial and economic research). Infrastructures across the continuum provide services such as training, methods development, data management, databases, software and/or access to analytical tools or methods. Infrastructures are also present in the sector that specialise in analytical tools or methods, or research services. The diversity of infrastructures means that categorisation can only be done in broad terms according to the following six groupings:

Data collection and services (e.g. Administrative Data Research Partnership)	Specific capability infrastructures (e.g. British Election Study)	Broad remit capabilities (e.g. Centre for Longitudinal Studies)
Historical, cultural and heritage collections	Creative and performing arts	Languages and literature

The sector as a whole contains a significant number of large, long-established infrastructures and those based on even longer established collections. Many of these are in the arts/humanities/heritage sector. The data presented in this chapter are derived from our questionnaire and supported by community consultations around the infrastructure roadmaps and previously performed sectoral reviews (such as the 2017 Longitudinal Studies Review[31]).

Gaps and coverage

Some disciplines within SSAH are less familiar with using the term ‘infrastructure’ to describe their research services or facilities and may have been slower to engage than other sectors, which could lead to gaps in coverage. Infrastructures that engaged were a mixture of targeted and self-identified infrastructures, so gaps may have occurred where individuals were unsure if they met the definition of infrastructure. This is likely to be more prevalent at the regional rather than national level. It is at this stage unclear whether the absence of particular areas (for example, education research-related infrastructures) is because the discipline does not have established discipline specific infrastructures, or that those infrastructures exist but to date have not been captured in this analysis.

There is considerable multi-disciplinary working between SSAH and other sectors. For example, there are a number of infrastructures concerned with cohorts and longitudinal studies that have significant interest in the BH&F sector (for example, the Cohort and Longitudinal Studies Enhancement Resources, CLOSER).

The SSAH sector has many infrastructures where the majority funder falls outside the research councils of UKRI. Other funding sources used in the sector include Quality Related (QR) block funding awarded to host universities, private or philanthropic funding sources, and for some infrastructures major public sector funding sources include other government departments (particularly Department of Culture, Media and Sport [DCMS]) and academies (e.g. British Institute projects funded by the British Academy).

Cohort and Longitudinal Studies

The UK is recognised globally as having significant strengths in longitudinal data, thanks to historic investments by UK research councils and other funders over many decades. The investment in these resources gives the UK research community a competitive advantage in understanding critical population trajectories over the life course and across changing contexts. A combination of longitudinal cohort and household panel studies covers the most urgent research questions of the scientific community and provides an adequate data landscape to study a broad range of research and policy related questions on different aspects of the life course.

Longitudinal evidence supports welfare to work policy and changes common perceptions of mothers who return to work

Research using the birth cohorts (NCDS, BCS70 [and their offspring], ALSPAC, MCS, Children of NLSY and BHPS) investigated the relationship between mother's employment and child outcomes, helping to change the prevailing presumption that children are affected from mothers going out to work, for which it found little evidence beyond the very early years. The research found a mother's employment and her circumstance and characteristics to be linked prospectively to the child's outcomes at a later date.

The research has been influential in challenging assumptions and to changing government thinking, including research carried out by Prof Heather Joshi in collaboration with Harriet Harman MP. This went on to support the development of policy on maternity and parental leave resulting in a report by the Smith Institute, for the government, being published 2000. The findings were cited by the Department of Trade and Industry Green Paper, Work and Parents[32]: 'Competitiveness and Choice in support of policies on flexible employment and leaves for parents' which continued to evolve into the 2010's.

Research using National Child Development Study (NCDS) data influenced policy thinking in establishment of world's first universal children's savings scheme totalling £4.8 billion

Research using NCDS data discovered that having even very modest savings at age 23 had a wide range of beneficial economic, social and health effects 10 years later. HM Treasury used these findings to create the Child Trust Fund which will benefit approximately six million UK children born between 2002 and 2011 to ensure that every young person had some savings at age 18.

Findings influenced HM Treasury papers presenting options for policies designed to increase rates of saving and asset-ownership, both among lower-income households, and in generations of families in the future, such as the 'Saving and Assets for All: The Modernisation of Britain's Tax and Benefit System'[33].

Current landscape[vi]

The infrastructures in SSAH make up approximately 15% of infrastructures engaged with (Figure 5.1). In common with other sectors infrastructures are split between being based at universities and independent research organisations.

A major sector theme is provision of access to research objects, such as archives, collections or data (Figure 5.2). In addition, infrastructures also provide access to research services, e.g. data management, training and methods development and support for data access. Some infrastructures also provide access to analytical tools, e.g. instrumentation or software. These are mainly provided in combination (e.g. the same provider will provide access to data and analytical software, e.g. EuroCohort) but there are infrastructures within the sector that specialise in services or analysis/ instrumentation.

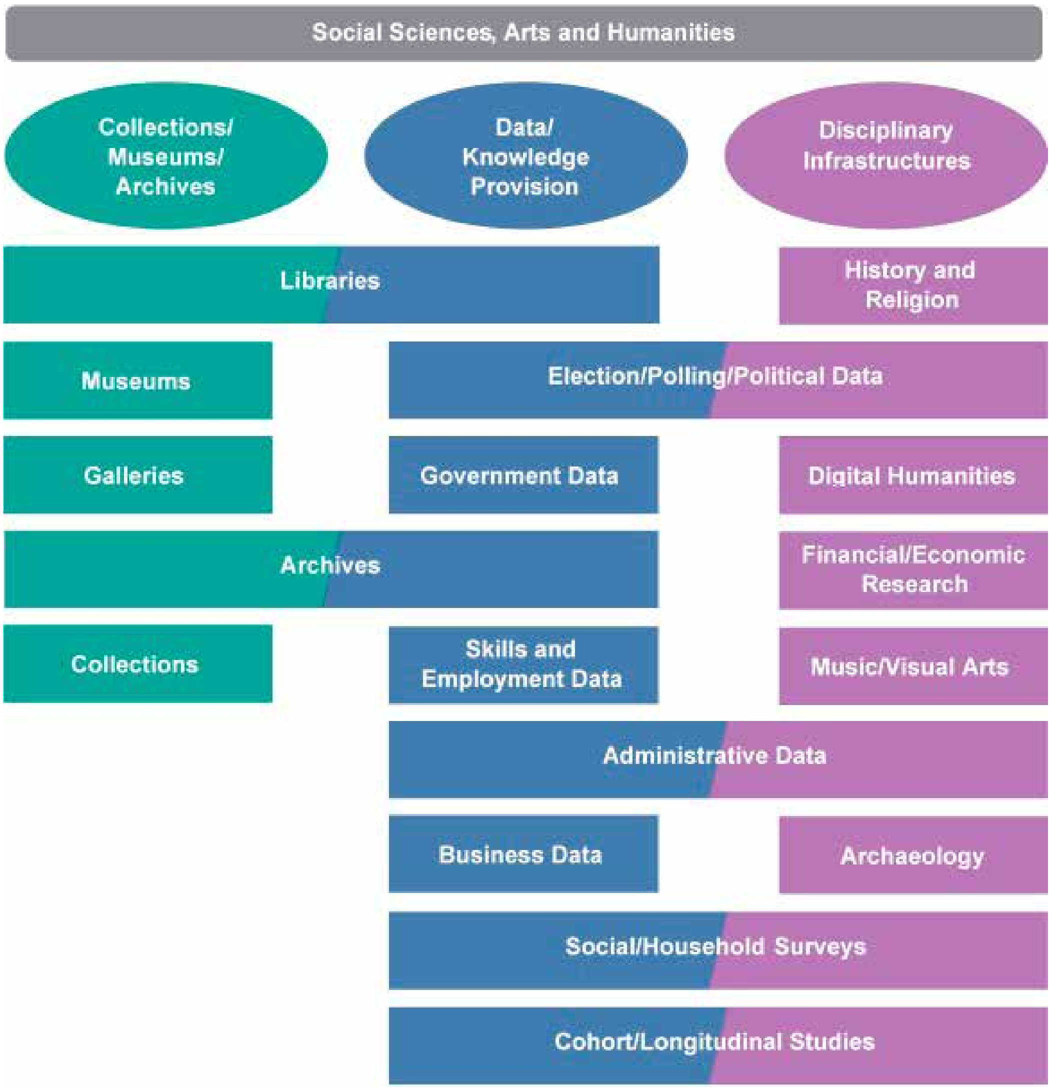


Figure 5.2. Schematic Diagram illustrating the disciplinary spread of SSAH infrastructures. The spread of provision runs from underpinning infrastructures that serve multiple disciplines and communities, such as libraries, collections and libraries, to infrastructures specialised to support particular disciplines or research areas.

[vi] The data presented within the SSAH chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which 6 identified SSAH as their primary sector.

As a number of SSAH infrastructures provide access to physical research objects in museums, galleries, archives and collections, 50% of the infrastructures in the sector operate on a single physical site (Figure 5.1c). A significant number provide access to data only and exist as data-centric infrastructures. twenty-six per cent reported their structure as 'hybrid'. This is a reflection of ongoing efforts to digitise physical collections (for example by the National Gallery) and requirements to access safe/secure data 'in person'.

The sector includes a significant number of large, long-lived research and innovation infrastructures (Figure 5.1b) of which 35% started operations prior to 1978. Most (92%) are currently in an operational phase. The picture is of a sector comprised of mature infrastructures.

Research and innovation infrastructures within this sector are recognised globally as leaders in their field or providing access to resources not replicated elsewhere (and in many cases, both). Eighty-six percent of infrastructures reported an international reach and 97% attract users based in other countries. The infrastructures include a number of British Schools and British Institutes that are housed outside the UK. They are highly (87%) collaborative nationally and internationally. It should also be noted that as well as academic researchers, the public are significant users of these infrastructures, as are both the government and third sector.

Links to the wider economy

Most of the infrastructures in this sector perform some work with business, with educational services cited as the most common economic sector contributed to (Table 5.1). Over 60% also support the creative industries. However, in terms of impact, a major component is contributions to policy development in government and the third sector, with most (60%) of the infrastructures reporting a contribution to public policy alongside related areas such as social services and health services (e.g. the Understanding Society studies that are run by the Centre for Longitudinal Studies).

E-infrastructure and data

The SSAH infrastructure sector has a significant presence of e-infrastructure services and platforms. For the majority of infrastructures (68%) e-infrastructure is an essential tool for their existence. This can be in the form of a digital platform or service, such as data curation or database management, analytical services (visualisation, data analytics, modelling and simulations) or both. A further 12% consider e-infrastructure as the primary discipline of the infrastructure. The requirement for e-infrastructure in SSAH infrastructures is expected to increase over the next five to ten years.

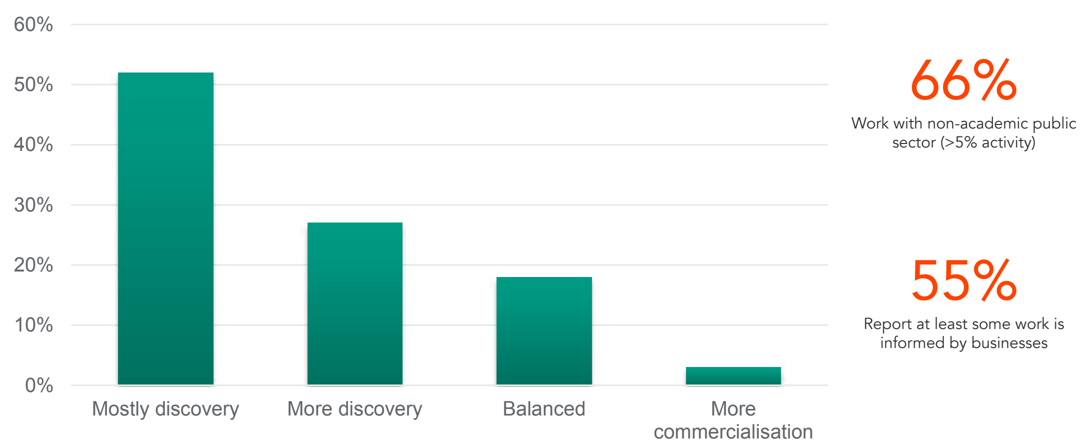


Figure 5.3. The spread of SSAH infrastructures on a discovery to commercialisation spectrum.

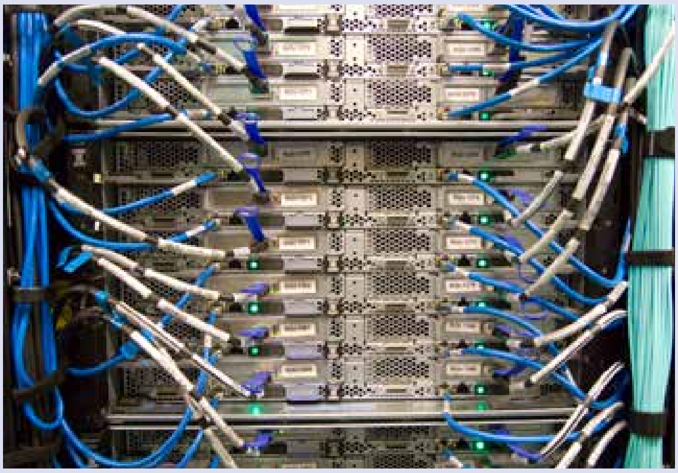
Table 5.1. Top eight economic sectors that SSAH infrastructures work with.

EDUCATIONAL SERVICES	CREATIVE INDUSTRIES, RECREATION	PUBLIC POLICY	SERVICES SOCIAL
85% (91)	63% (67)	60% (64)	44% (47)
COMMUNICATIONS & INFORMATION	HEALTH SERVICES	COMPUTING	RESEARCH & ENGINEERING
40% (43)	36% (39)	30% (32)	30% (32)

The Department for Work and Pensions (DWP) used Understanding Society, a longitudinal household questionnaire and the Millennium Cohort Study (a birth cohort study) to build an understanding of the multiple disadvantages that workless families often face and the impacts these disadvantages have on children and young people. Proposals based on the findings include redefining the **Troubled Families Programme** "to encourage a greater emphasis on tackling worklessness and issues associated with it" and strengthening support to help reduce relationship distress between parents/carers, whether together or separated.

An innovative new programme followed, backed initially by £30 million (April 2017), with an additional £12 million added in the November 2017 Budget Statement.

The Urban Big Data Centre (UBDC). Strava, world-leading providers of fitness apps, have designated UBDC as their UK distributor of Strava Metro cycling data[34] for use in research. This is crucial to their business model and core to their mission to make riding, running and walking in cities better. In 2017 they supported the UBDC Active Travel Data Challenge, and attended a hugely successful Data Demo Day, which attracted participants not only from the public, government bodies, cycling activist communities and third sector groups, but also small consultancies and large planning multinationals.



The UBDC data collection currently makes available several years' worth of Strava Metro data about cyclists' journeys in Scotland (including data back to 2013 for Glasgow only), Manchester, Tyne & Wear and Sheffield. UBDC researchers have validated this data as a useful basis for understanding cycling habits and have used it across a wide range of projects supporting transport planning and public health policy. Thanks to the generous licensing of this it is used by external researchers, planners, government bodies at all levels and cycling activists. Strava have agreed to continue this partnership into UBDC Phase 2 from 2019-2024.

Victoria and Albert Museum - The Clothworkers' Centre for the Study and Conservation of Textiles and Fashion

The Clothworkers' Centre is a state-of-the-art facility that offers a unique opportunity to inspect and study one of the most important collections of textiles and fashion in the world, ranging from archaeological fragments to heavy tapestry and carpets, accessories and underwear to embroidered 18th century court dresses and contemporary haute couture.

Since its establishment five years ago it has hosted over 14,000 individual visitors. Of these approximately a quarter (27%) come from fashion or related industries, including Dior and Erdem, which draw upon the collections as a source of inspiration in their own designs.

The actual historical garments are used for new ideas for collections or for construction methods. There is considerable interest in the fashion industry in historical techniques for garment construction, e.g. Balenciaga tended to drape, cut and stitch onto an upright mannequin rather than from a pattern, so the only way to reproduce the techniques is to study the garment. To date, attempts to create a software package to 'reverse engineer' the process have not been successful. There is also considerable interest in dye composition and technique. The archive is also used by fashion writers when preparing articles.

Chapter 6: Environmental sciences sector

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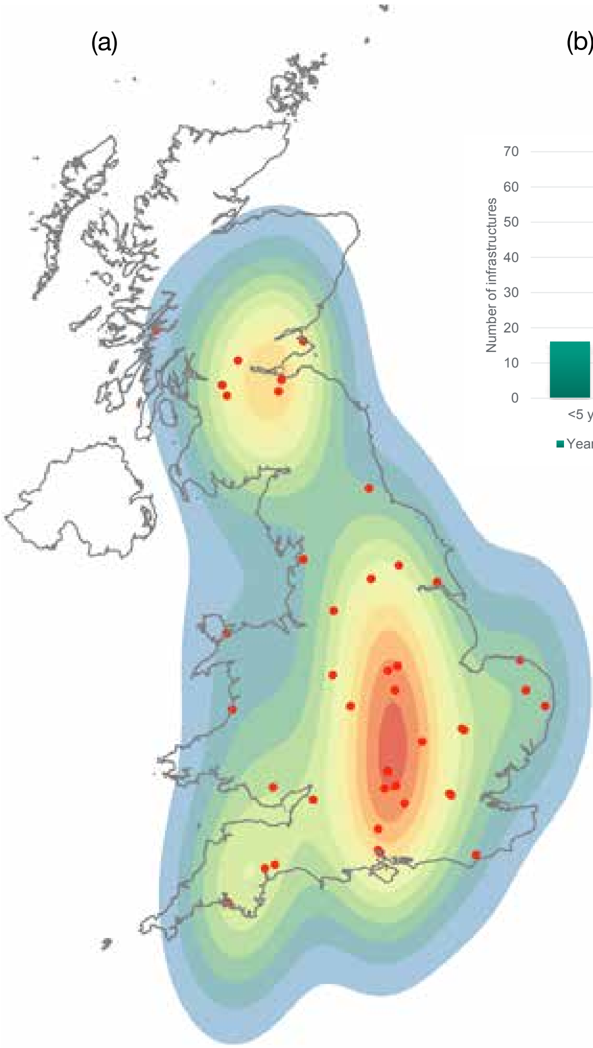

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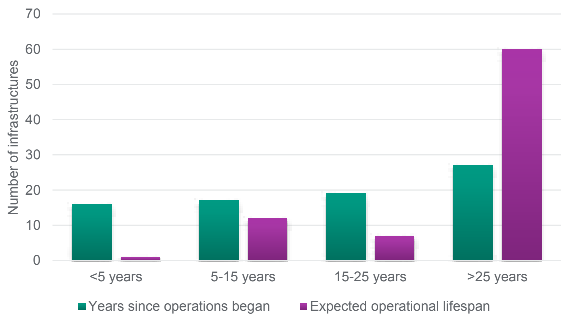


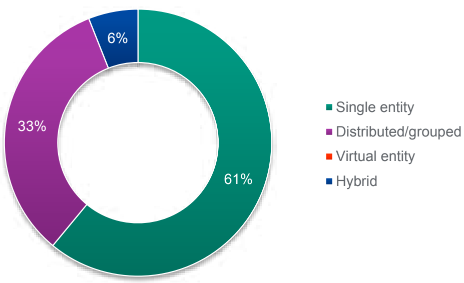
80 / 755

OF INFRASTRUCTURES DESCRIBE THEIR MAIN DOMAIN AS ENVIRONMENT

60%

OF ALL OTHER INFRASTRUCTURES COVER ENVIRONMENT

(c)



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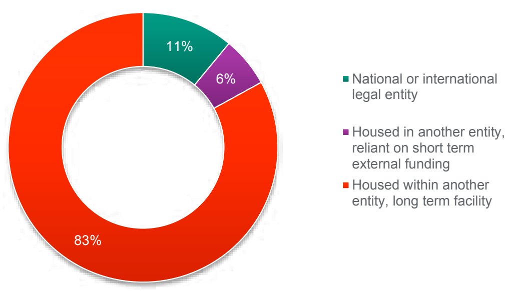


Figure 6.1. (a) The geographical location of infrastructures in the Environment sector across the UK. Red dots can indicate individual infrastructures or clusters at one location, red colours indicate highest densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/distributed entities or virtual (digital). (d) The distribution of infrastructures according to their legal structure.

Overview

Environmental scientists study and monitor the physical, chemical and biological processes on which our planet and life itself depends and which cut across these 'compartments' of the Earth system. The Environment sector includes terrestrial, freshwater, marine, science-based archaeology, atmospheric, climate, and polar sciences, together with Earth observation. As a result, the Environmental infrastructures span the full range of size and complexity and include ships, aircraft, high performance computers and advanced modelling, data assimilation and analysis software, laboratory-based analytical facilities, *in situ* measurement networks, farm- and landscape-scale experiments and collections such as geological cores/geoscience data sets. A characteristic of the Environmental sector is the breadth of scales from the nano to planetary, from seconds to millions of years, and the harsh and hazardous environments often encountered. The extensive range of Environmental infrastructures are as diverse and varied as the science challenges they address. Environmental infrastructures cut across compartments of the earth system, and are designed, supported and delivered in partnership with multiple research funders and research users.

Given that the questionnaire responses do not cover the complete breadth of the Environmental sector, the narrative in this chapter also draws on expert workshops and discussions with the community.

Current landscape[vii]

Eighty of the infrastructures who responded to the questionnaire identified their macro-domain primary field as Environment (Figure 6.1). Furthermore, 60% of other sector infrastructures identified Environment as a domain their infrastructure covered, where these infrastructures are fairly evenly split across the entire UK R&I sectors as shown in Figure 6.2. This evidences the breadth and scope of the Environmental sector and highlights the cross-cutting nature of it's infrastructures. For example, three quarters of infrastructures which identified their primary sector as E-Infrastructure also identified the Environmental sector as a secondary or subsequent domain.

Research fleet

NERC owns several research ships that support complex, multidisciplinary research and include state of the art technology and instruments to provide research needs across all the disciplines. The ships enable oceanographic research in the most extreme and remote oceanic environments on Earth. Over 15 years of NERC investment has created the largest and most diverse fleet of robotic research vehicles in Europe, including ten thousand items with a collective value estimated at £20 million. NERC unmanned marine vehicles go further and deeper than any commercial or military capability.

Credit: National Oceanography Centre

The RRS Discovery and autonomous vehicles

[vii] The data presented within the Environment chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which two identified Environment as their primary sector.

The infrastructures within the environment sector are broad, diverse, and geographically distributed across the country, as shown in Figure 6.1a. Eighty-two per cent of Environmental infrastructures are located outside of London and the South East, compared to the all-sector average of 75%. Nearly two-thirds of infrastructures are single site focussed, with around a further third identified as distributed or grouped (Figure 6.1c).

The global challenges we are facing require global solutions. Working in an international arena and partnering internationally is a key characteristic of the environment science community and the infrastructures that support it. The overwhelming majority of Environmental infrastructures (96%) collaborate with other infrastructures and organisations and 83% collaborate internationally. This wide collaborative scope is further evidenced by 91% of infrastructures attracting users from other countries. This high-level of attraction on the international stage is due to a better overall package (58%), unique capability (52%), the infrastructure being part of an international collaboration (43%) and the quality of the infrastructure (38%). 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 €74 million cost to build EISCAT_3D.

Environmental infrastructures are often of national and international importance and uniqueness. Over half (54%) of infrastructures stated their users would have to travel outside of the country to access a similar capability. Most importantly, nearly a third (30%) identified that there was no other similar capability in the world, including Birmingham Institute of Forest Research Free Air Carbon Enrichment Facility and Svalbard Integrated Arctic Earth Observing System.

The Environment sector had the highest number of infrastructures (75%) with an expected operational lifespan of over 25 years, compared to an average for all sectors of 58%. Continuity of long-term infrastructures for sustained observations and the collection of long-term data sets is vital for the Environment sector, such as the Met Office Observations Network that has been in operation since 1853. The vast majority of Environmental infrastructures (95%) are in operation.

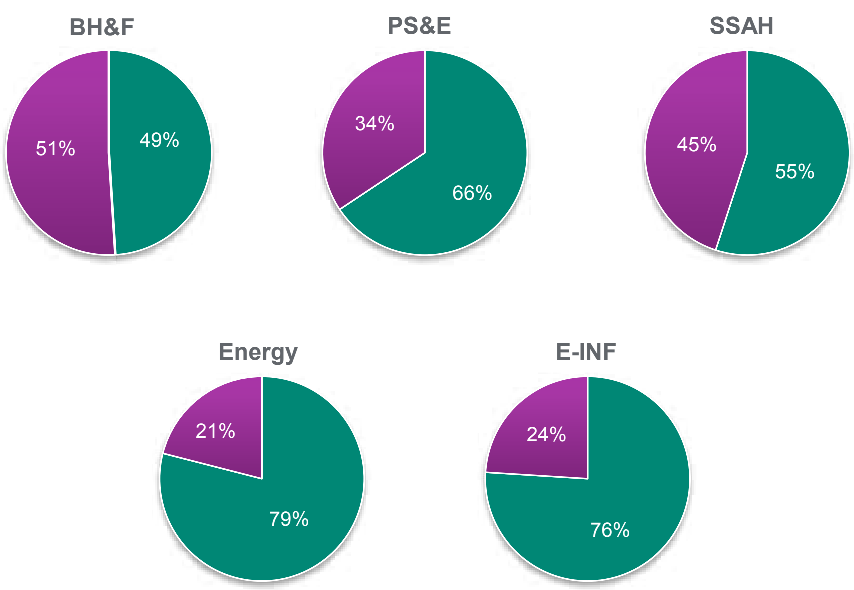


Figure 6.2. The percentage of infrastructures in other primary macro-domains which identified ENV (shown in green) as a domain their infrastructure identifies as.

Links to the wider economy

Environmental science underpins all economic, industry and policy sectors. This is reflected in the association of Environmental infrastructures with economic activity from public policy, agriculture, mining to health services (Table 6.1). Additionally, 71% of Environmental infrastructures work directly with UK businesses (Figure 6.3). Almost two-thirds of Environmental infrastructures (64%) provide resources and/or related services to the wider community in addition to providing the infrastructure itself.

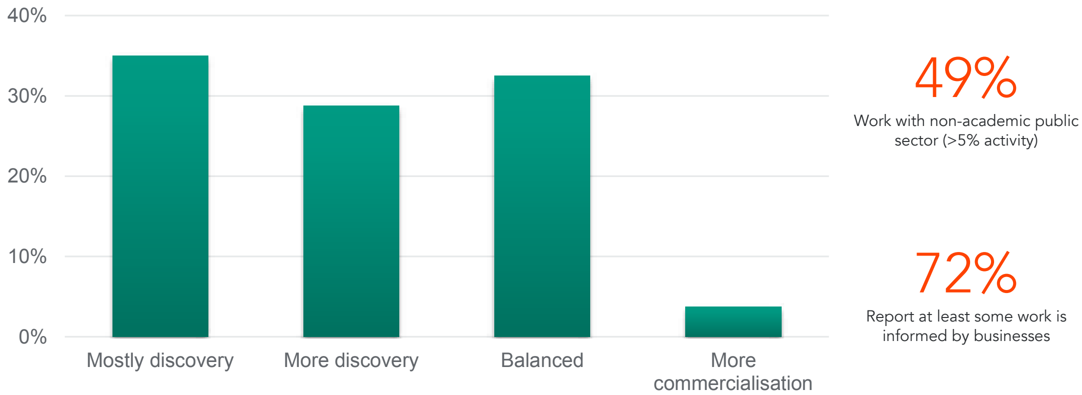


Figure 6.3. The spread of Environmental infrastructures on a discovery to commercialisation spectrum.

Polar infrastructure and sustainable fisheries

For more than 30 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've 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 a large area of the Ross Sea region being designated a Marine Protected Area and the virtual elimination of seabird mortality associated with fishing.

Credit: British Antarctic Survey

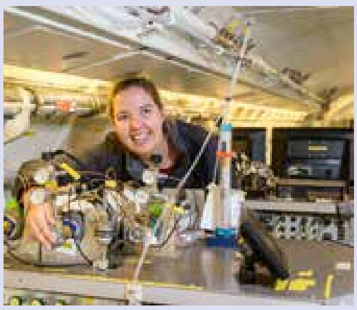
Table 6.1. Top eight economic sectors which ENV infrastructures work with.

RESEARCH & ENGINEERING	PUBLIC POLICY	ENERGY	AGRICULTURE
66% (53)	55% (44)	53% (42)	50% (40)
EDUCATIONAL SERVICES	**FISHERIES**	**FORESTRY**	**MANUFACTURING INSTRUMENTATION**
45% (36)	41% (33)	35% (28)	28% (22)

Atmospheric infrastructure

Following the eruption of Eyjafjallajökull 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 the Facility for Airborne Atmospheric Measurements (FAAM), avoided the unnecessary closure of UK airspace and saved airlines £290 million per day.

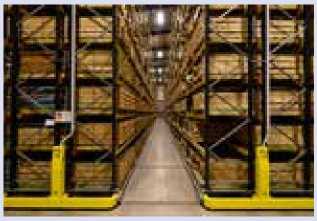
FAAM is Europe's largest flying atmospheric laboratory housed in a modified BAe 146-301 aircraft. The aircraft carries a large and versatile suite of instrumentation to characterise processes throughout the troposphere up to around 10 km altitude. Barring Antarctica, it is capable of operating anywhere in the world. The FAAM facility 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.



Credit: Centre for Atmospheric Science, plane - UKRI

The **National Geological Repository (NGR)** contains collections of geological materials curated over the past two centuries including:

- Over 200 km of cores, samples and cuttings from over 15,000 boreholes
- Over 300 km of drill-core and 4.5 million samples of cuttings from approximately 8000 wells
- Offshore sea-bed sediment and core samples
- Over three million micro and macro fossils
- The major British collection of rocks
- Geochemistry materials
- Vast logs and data collections
- The British Antarctic Survey's rock and fossil collections


Credit: British Geological Survey

These collections are managed in the NGR for the benefit of researchers and innovators in industry, academia and the public. The core collection has more than 23,000 rock cores from around the UK available for inspection. These have been used, for example, by energy firms to avoid unnecessary drilling costs of around £12 milllion per well. The NGR collections are being scanned and digitised and made available online. Examples include over 1.3 million scanned UK onshore borehole records, and 125,000 high-definition images of cores from UK continental shelf hydrocarbon exploration and production wells.

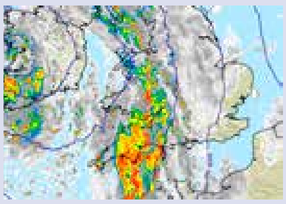
E-infrastructure and data

The majority of environmental challenges use techniques based around modelling, simulation and observation in some form or another.

There is an increasing need to manage large, interoperable datasets and associated challenges, such as data quality. The environment sector has world-leading data analysis and storage infrastructure in JASMIN, and globally competitive high performance computing capabilities through ARCHER, NEXCS and MONSooN/Monsoon2. JASMIN is a globally unique data intensive supercomputer for environmental science and currently supports over 160 science projects. JASMIN users' research topics range from earthquake detection and oceanography to air pollution and climate science. JASMIN has available storage of more than 44 Petabytes, equivalent to storing over 10 billion photos.

The majority of Environmental infrastructures (76%) are associated with e-infrastructure. In addition to this, over three-quarters (77%) envisaged e-infrastructure and data becoming more relevant to the infrastructure in the next five to ten years.

MONSooN and its successor Monsoon2 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, fast data link and access to data archives.


© Met Office

Incorporating atmospheric measurements from FAAM in Met Office weather models have improved accuracy and helped the Environment Agency, the NHS, local authorities, agriculture and transport to address weather related challenges, e.g. (i) £76 million-£127 million per year reduction in flood damage, (ii) reduction in the £500 million per day cost to the economy of heavy snow, and (iii) reduction in cold-weather related deaths among vulnerable people and in unnecessary stockpiling of road salt. More accurate and earlier flood warnings during the winter storms of 2013-2014 protected a million homes, saved £2 billion in UK insurance pay-outs and avoided £2.6 billion of lost working in London.

Chapter 7: Energy sector

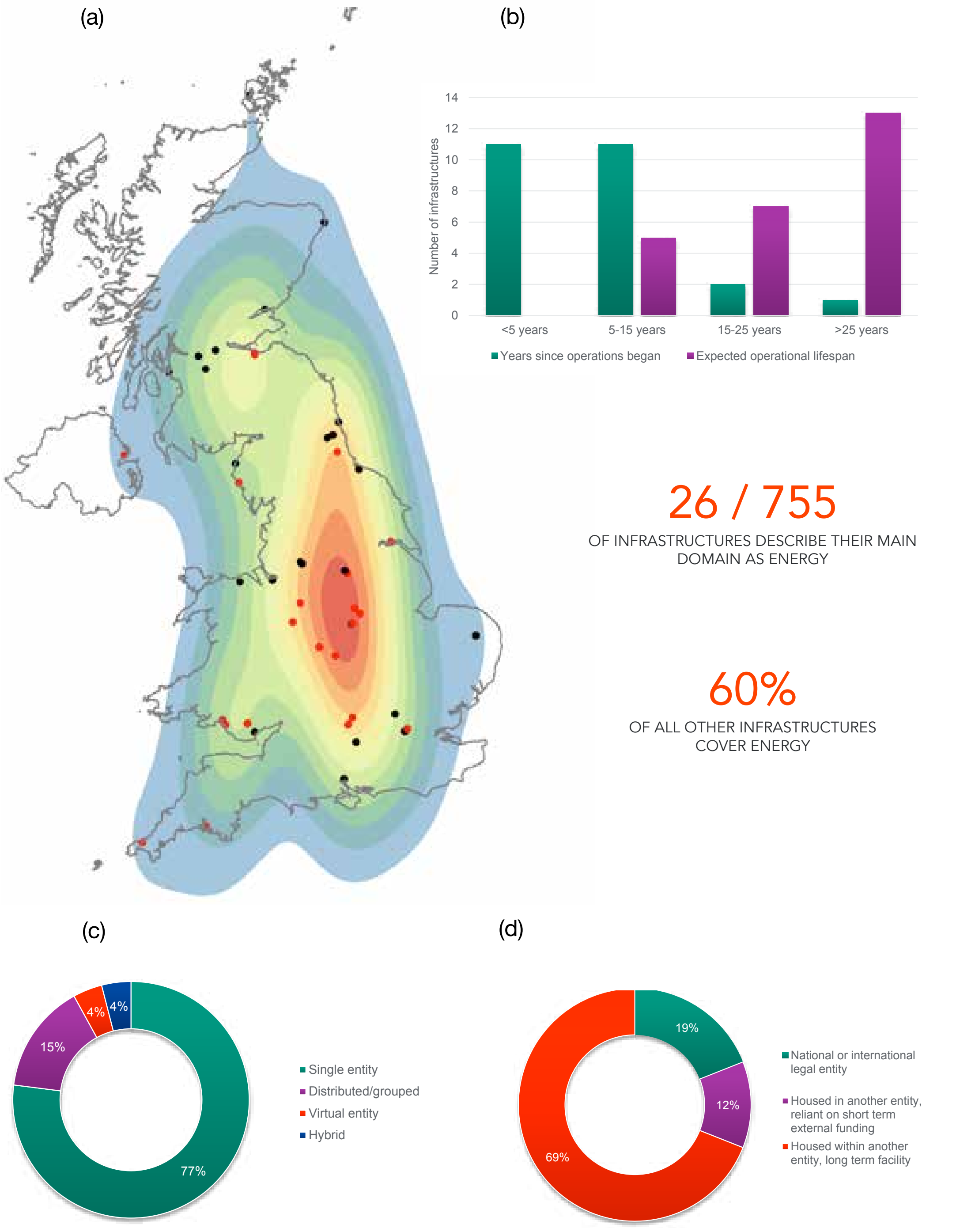


Figure 7.1. (a) The geographical location of infrastructures in the Energy sector across the UK. Red dots indicate individual infrastructures or clusters at one location identified through the Questionnaire, black dots indicate individual infrastructures or clusters at one location identified through other means, red colours indicate highest overall densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/distributed entities or virtual (digital). (d) The distribution of RIIs according to their legal structure.

Overview

Energy infrastructures cover several diverse sub-areas including power systems, nuclear, carbon capture and storage, energy storage, renewable energy sources (wind, marine, wave, tidal, solar and geothermal), alternative fuels, hydrogen, oil and gas, gas turbines, demand (from buildings, transport and industry) and energy models, in addition to the whole energy system and demonstrators. Within each of these sub-areas the research requirements are also often multidisciplinary, for example bringing together electrochemistry, materials science, systems engineering and advanced manufacturing to develop low cost, sustainable and reliable energy storage.

This chapter presents a picture of publicly funded Energy infrastructures.

Energy R&D in the UK involves cutting-edge research to address key high level challenges including:

- Development of new energy technologies/ solutions affordable for the public
- Transition to a sustainable-resilient-low carbon integrated reliable and flexible energy system
- Integration of various renewable energy sources into the energy system
- Decarbonising sub-sectors of energy including heat, transport, power and industry
- Development of energy storage in all the energy vectors including electricity, gas, heating and cooling that will be needed for an energy system with a substantial proportion of renewable energy

Gaps in coverage

This description of the Energy sector has been derived from responses to the questionnaires plus interviews with key energy experts, expert elicitation workshops and an evaluation of existing key reviews conducted by CESI[viii] on behalf of the infrastructure roadmap programme. The data presented here relate to that derived from questionnaires unless otherwise indicated. However, additional insight gained from the interviews and workshops has been used to develop the overall narrative of the current Energy infrastructure landscape to improve our understanding of the sector.

Based on the expert consultation workshops, interviews and the existing key reviews the current landscape of the Energy infrastructures is summarised in Table 7.1. Given the more focused topic area, the Energy sector consists of a relatively small group of infrastructures. However, energy research is multi and interdisciplinary in nature and a significant number of infrastructures within other sectors provide necessary fundamental science and address broader challenges linked to energy issues. As well as the core engineering and physical science requirements this sector requires an understanding of how the macro level energy system functions and is used.

The areas where infrastructures engaged actively via the questionnaire include energy storage, whole energy system, energy system demonstrator, carbon capture and storage and alternative fuels. Areas where coverage was poor include power systems and wind and solar renewable energy sources.

[viii] EPSRC National Centre for Energy Systems Integration.

Table 7.1. Research and innovation infrastructures in the Energy sector.

Area of the Energy infrastructure (in the UK)	Responded to UKRI survey	Identified by CESI[ix]	Total
Whole energy system			
• Interdisciplinary	1	3	4
• Gas turbine	1	0	1
• Building	2	2	4
• Energy models	1	0	1
• Oil and gas	1	0	1
Power systems	0	5	5
Energy system demonstrator	1	1	2
Nuclear	3	4	7
Carbon capture and storage	1	1	2
Energy storage	3	0	3
Renewable energy sources			
• Wind	1	4	5
• Marine	3	5	8
• Solar	0	3	3
• Geothermal	0	0	0
Alternative fuels	2	2	4
Hydrogen	0	1	1
General Infrastructures	6	1	7
Total	26	32	58

[ix] Identified by CESI through workshops, interviews and key reviews and not currently captured by the questionnaires.

Fusion Energy infrastructures at UKAEA

Credit: EUROfusion

The 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.

The **Joint European Torus (JET)** infrastructure at Culham makes up the world's largest magnetic fusion experiment and is also the largest EU facility in the UK. JET 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. The JET facilities are collectively used by all European fusion laboratories under the EUROfusion consortium. JET is operated by over 500 staff and more than 350 scientists and engineers from Europe and beyond use the infrastructure for their experiments each year.

Mega Amp Spherical Tokamak (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.

Credit: UKAEA

Over 30,000 man-made 'stars' have now been created by experiments inside MAST. The wealth of data created has enabled advances in key research areas. This is assisted by MAST's suite of diagnostics for analysing plasmas.

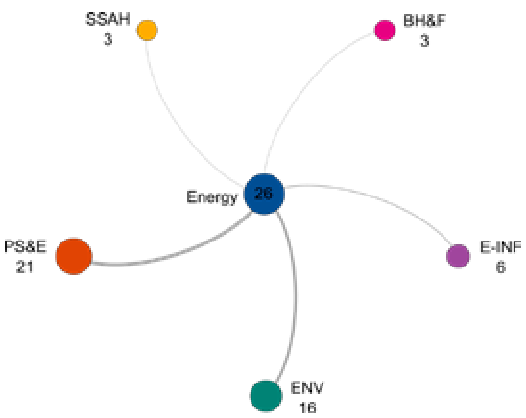
Credit: Monty Rakusen

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 National Nuclear User Facility (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.

Current landscape[x]

Twenty-six of the infrastructures engaging through the questionnaire identified Energy as their primary sector. Fifty-one percent of the remaining infrastructures stated they also cover Energy as a part of their remit. This indicates that there is a strong link between Energy and the other infrastructures sectors (Figure 7.2). Very few survey responses were identified from infrastructures in the sub-sectors of Energy such as power systems, nuclear, carbon capture and storage, energy storage, renewable energy sources, alternative fuels, hydrogen, oil and gas and interdisciplinary research.

Of the infrastructures that identify as mostly Energy in focus the greatest overlap is declared to be with the Environmental and the PS&E sectors, with smaller numbers overlapping with BH&F, SSAH and E-Infrastructure. This correlates strongly with the levels of overlap shown by those infrastructures that are not primarily energy with energy as a research area.



The plot shows the overlaps between the Energy Primary Macro-domain and other Macro-domains selected.

The peripheral nodes represent the remaining Macro-domains, and their sizes relate to the proportion of their overlap with Energy Primary Macro-domain (co-occurrence) based on the number of responses that selected each Macro-domain.

Figure 7.2. Interdisciplinary working between infrastructures that identified Energy as their primary sector and other infrastructures[xi].

The contour map (Figure 7.1a) shows that the Midlands is highlighted as the area of greatest density of Energy infrastructures. However given the overall small sample size and corresponding large contours a fairer conclusion is that the facilities are quite distributed throughout the UK.

Of the infrastructures identifying Energy as primary sector, 73% were also relevant to the Environmental sector. For example Energy is the primary sector of ECCI (Edinburgh Centre for Carbon Innovation), and Ergo (East Riding of Yorkshire Council), but they also identify strongly with Environment as well. Strong connections between the PS&E sector and Energy infrastructure were also evident with 71% of Energy infrastructures including PS&E as a sub-domain. SPECIFIC (The Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings) and NNL (National Nuclear Laboratory) both mentioned that Energy is their primary sector, whilst they also cover PS&E. PACT (Pilot-scale Advanced Technology) and PRL (Pyrochemical Reprocessing Laboratory) cover PS&E and Environment sectors while energy is their primary focus.

Many of the infrastructures in the Energy sector are relatively new (Figure 7.1b) with 85% starting operations within the last 15 years. This could be due to the increased investment in energy that has taken place over the last 15 years in response to energy challenges. For example, the UKRI energy programme spend has increased from c. £30 million per annum to c. £180 million per annum since 2004. The Energy Technology Institute was created in 2008 with an indicative budget of up to £100 million per annum. Also, within this time the UK pledged to double energy R&D to £400 million per annum.

As with most other infrastructures, the majority of Energy infrastructures are housed within another entity (Figure 7.1d), typically

[x] The data presented within the Energy chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which one identified Energy as their primary sector.

[xi] Acknowledgement: Sci2 Team. (2009). Science of Science (Sci2) Tool. Indiana University and SciTech Strategies, http://sci2.cns.iu.edu. Individual scaling applied.

universities, and are reliant on long term funding. These large centres that host energy research are often providing the underpinning scientific capability in areas such as materials research that need to be applicable across all sectors as it would not be cost effective for a dedicated energy focused legal entity.

Nineteen percent of the Energy infrastructures are national or international legal entities, which is slightly higher than most sectors. National entities such as the National Nuclear Laboratory (NNL) exist as dedicated facilities to serve a specific market that is sufficiently large or with unique challenges, that they can warrant being dedicated to a single energy research area. International facilities such as those within UKAEA can play a unique role in contributing to the UKs international obligations (e.g. Joint European Torus [JET]). They can also form a nucleus of expertise around which a national programme can coalesce, such as the Mega Amp Spherical Tokamak (MAST), the Materials Research Facility (MRF) and Remote Applications in Challenging Environments facility (RACE) at UKAEA.

The majority of Energy infrastructures (77%) are single-site physical entities, which again is higher than most other sectors. Many of the smaller, more highly focussed facilities, tend to be located in universities, such as the FloWave Marine Test Facility in Edinburgh University.

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 Institute bringing 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.

Links to e-infrastructure

E-infrastructure has a strong connection with the Energy sector and can help address the challenges of capturing data, modelling and simulation of various sub-sectors/ sub-systems of the Energy sector. For example, e-infrastructure can enable real-time monitoring of remote facilities (e.g. wind farms). Real-time monitoring is valuable for performance checks, early detection of fault and errors, and ensuring the security of the system is intact. E-infrastructure can also support a flexible heat and power requirement by predicting the demand and providing efficient load following.

Data are a valuable resource that can be used to inform models, improve accuracy of forecasting and cost optimisation, inform policy interventions and help businesses to develop. As with all sectors, e-infrastructure enables businesses or aggregators to have sufficient access to data, to enable more informed decisions. Smart energy systems encompass the integration of energy systems with e-infrastructure to bring together a variety of data, computing resources, and telecommunication technologies.

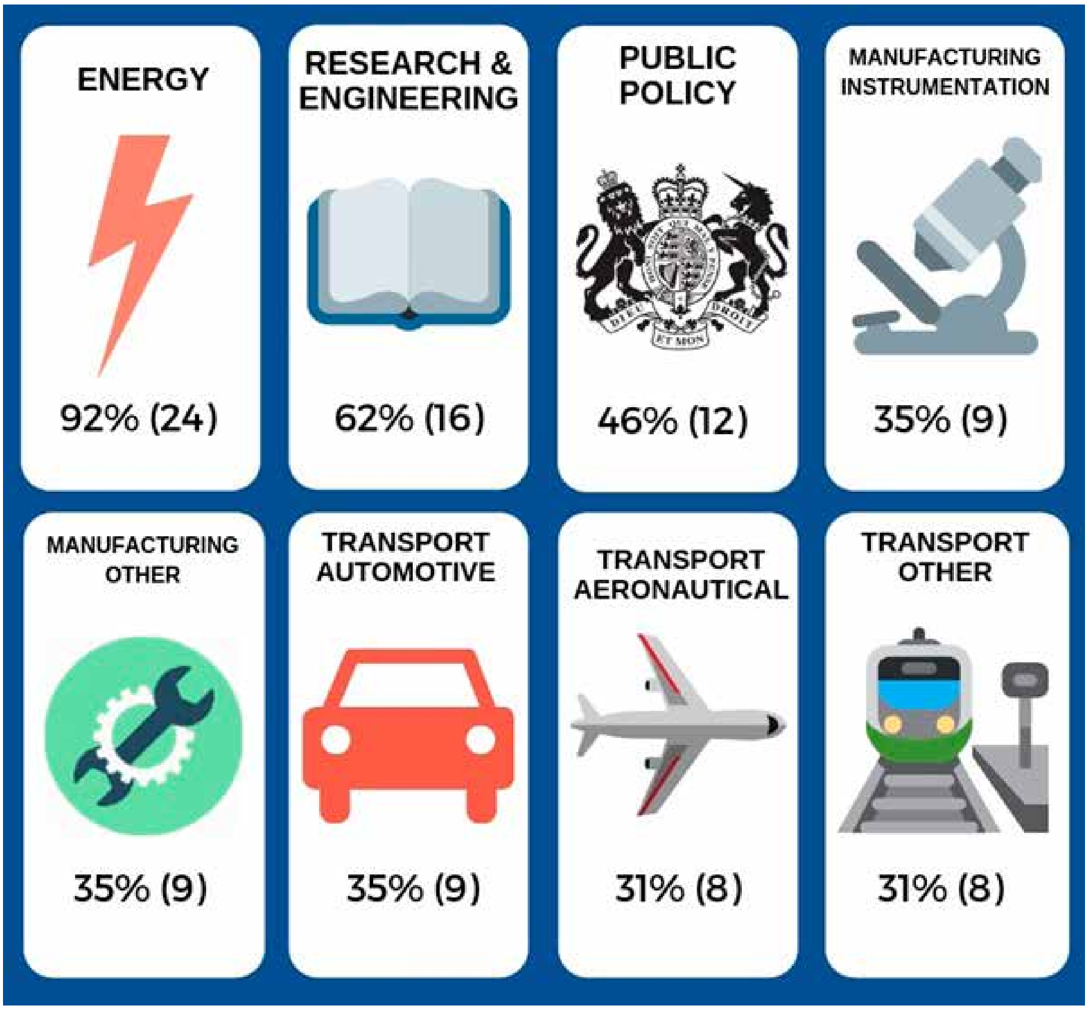
At least 63% of Energy infrastructures had a 'significant e-infrastructure/data requirement or component'. For all bar one of these, e-infrastructure and data were used as research tools to support their primary research rather than being primary purpose. Sixty-three percent of respondents considered that e-infrastructure and data would become more relevant over the next five to ten years.

In future energy systems, the integration of varied and new sources of data may pose challenges both in terms of storage and coordinated security policy, which can be solved by investing in the link between the E-infrastructure and Energy sectors. Future Energy infrastructures need to be linked digitally together to let them exchange data, models and results. E-infrastructure can also enable the digital twin technology for the Energy sector using the 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-E-infrastructure infrastructures.

Links to the wider economy

The Energy infrastructures are mainly seen as important to the utilities and the energy supply chain (Table 7.2). The other economy sectors that Energy infrastructures contribute to include public policy, transportation (automotive, aeronautical), manufacturing, instrumentation and the construction sector. This indicates that Energy infrastructures have a breadth of economic contributions, and have a role in reduction of emission since all the above sectors are important to help the UK Government meet carbon emissions reduction targets.

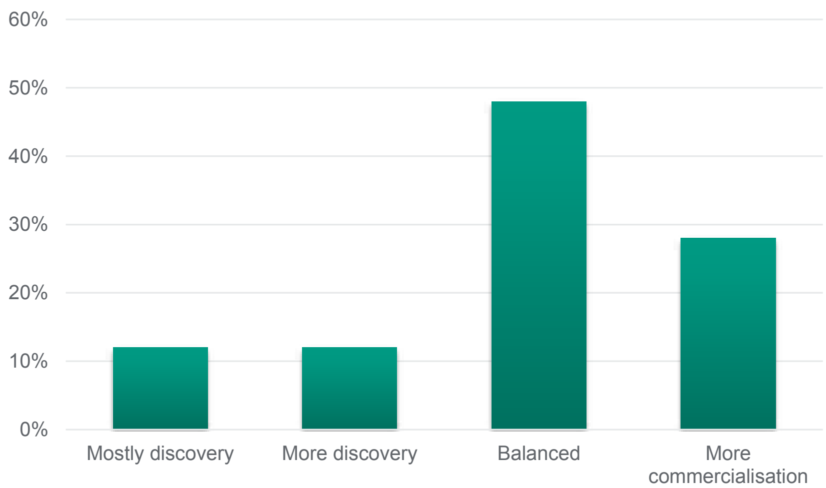
Table 7.2. Top eight economic sectors that Energy infrastructures work with.



Energy is the only sector where every infrastructure has some involvement with business and the highest skew in output towards commercialisation (Figure 7.3). Energy is an entirely regulated sector. Almost no energy generation technologies can be installed without either certification of the technology (nuclear) and/or permissions for installation (offshore renewables). This means energy technologies need to be thoroughly understood before they are allowed to market leading to requirements for technology development, testing and certification capability.

Most R&D focused infrastructures are largely publicly funded and the majority of development and deployment focused infrastructures are industry funded. Where there are more nascent markets there are parts of the sector that require government support for pre-commercial activity to prove and de-risk the technology.

Industry is faced with applied problems that the academic research base is well placed to help solve, and hence the energy industry actively collaborates with academia. Industry also uses infrastructures directly where there is more commercially sensitive R&D to be done. Much of the infrastructure would be too expensive and possibly underutilised if a company were to build it themselves, therefore most infrastructures represent a shared or pooled resource that is available to multiple industries and academia, and that draws on the UK academic expertise. Where infrastructures are cost and use effective for industry to build themselves they do so, such as InTEGRel which is led by Northern Gas Networks, and in partnership with Northern Powergrid and Newcastle University and is based in Gateshead.



53%
Work with non-academic public sector (>5% activity)

100%
Report at least some work is informed by businesses

Figure 7.3. The spread of Energy infrastructures on a discovery to commercialisation spectrum.

FloWave is a marine energy research facility constructed for cutting edge academic research into wave and tidal current interactions. The FloWave Ocean Energy Research Facility 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.

Credit: UKRI and Mr Stuart Brown

Chapter 8: Computational and e-infrastructure sector

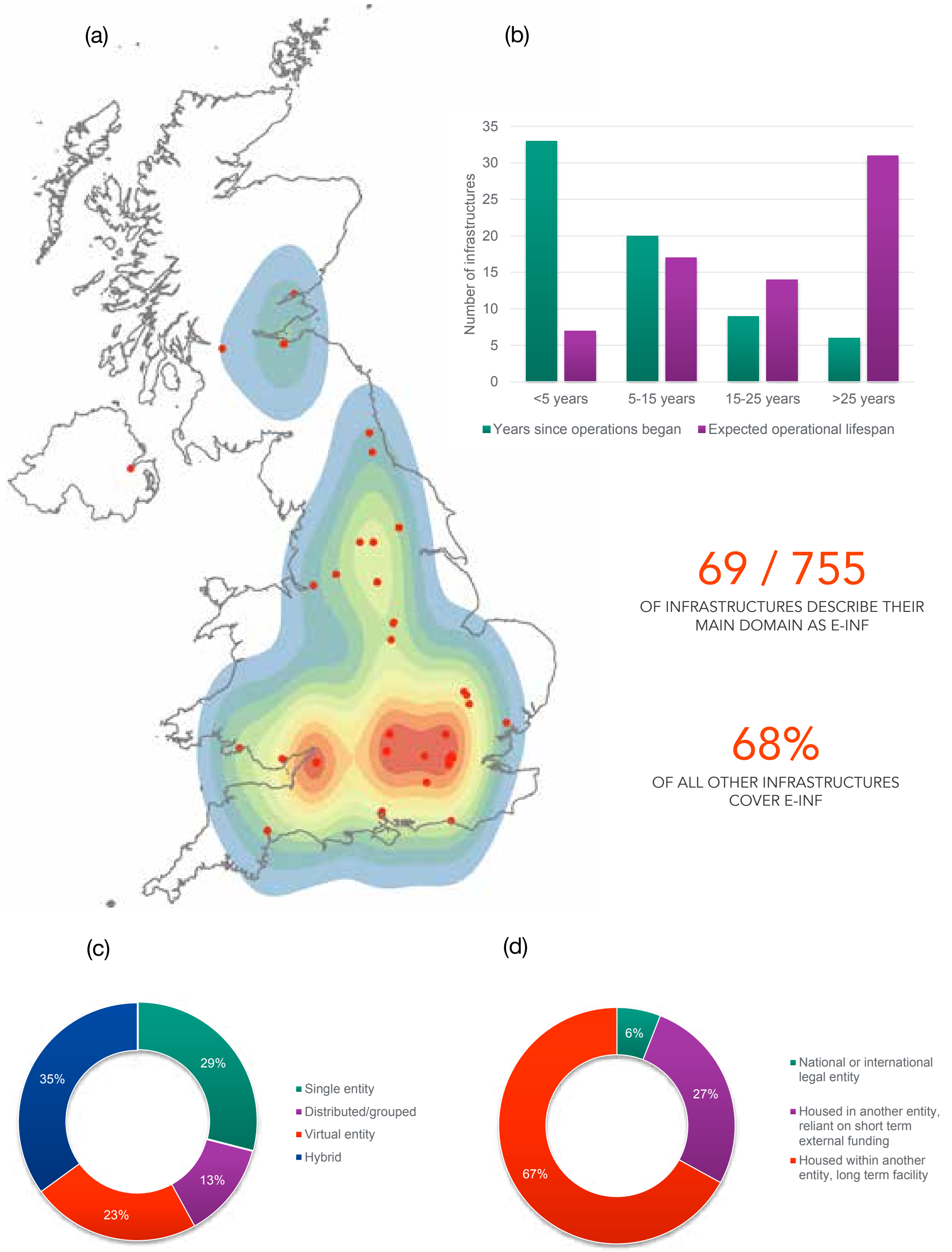


Figure 8.1. (a) The geographical location of infrastructures in the E-infrastructure sector across the UK. Red dots can indicate individual infrastructures or clusters at one location, red colours indicate highest densities and blue the lowest with smoothing applied across contours. (b) Infrastructures grouped according to their years of operations and their expected operational lifespan. (c) The distribution of infrastructures according to whether they are single entities, grouped/distributed entities or virtual (digital). (d) The distribution of infrastructures according to their legal structure.

Overview

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 networks
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

E-infrastructure is an important underpinning component of the research ecosystem across UKRI and is critical to the operations of a number of public sector bodies such as the Met Office. Jisc[xii] is responsible for the Janet network and a range of other digital resources and infrastructures such as identity management and information security.

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. This places the UK 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.

Sixty-eight percent of infrastructures from other sectors reported a requirement for E-infrastructure (Figure 8.1). It is likely that this underrepresents the actual requirement because computational and digital approaches are becoming ubiquitous across all fields of research.

[xii] 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.

Current landscape[xiii]

The E-infrastructure sector has strength in diversity, reflecting the diversity of the research needs. This degree of diversity defies easy categorisation, however, Figure 8.2 attempts to capture this.

At the centre of E-infrastructure are the people: both the academic and industrial users, plus 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 hardware, but do not dispose of their codes. It 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.

The use of e-infrastructure is significant across all sectors (Figure 8.3). It is used as a tool in over half of infrastructures in every sector that did not identify with e-infrastructure as their primary sector. It is a primary discipline in almost 20% of BH&F infrastructures and over 10% of SSAH and Environmental infrastructures.

Figure 8.2. The E-infrastructure landscape.

[xiii] The data presented within the E-infrastructure chapter relates to regional, national and international RIIs and is drawn from a sample of 755 questionnaire responses. Chapter 2 presents data on RIIs of national significance and greater only, thus excluding the 43 regional RIIs of which two identified E-infrastructure as their primary sector.

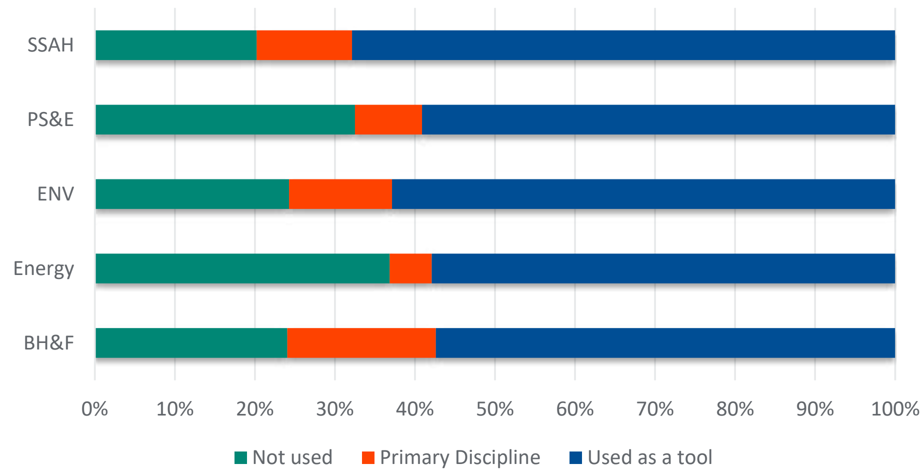


Figure 8.3. E-infrastructure usage by infrastructures in sectors that did not identify e-infrastructure as their primary sector.

The UK Data Service provides access to the UK's nationally and internationally significant social science data assets for research, teaching, skills development and policy-making.

The UK Data Service is funded by the Economic and Social Research Council to meet the data needs of researchers, students and teachers from all sectors, including academia, government, charities, think tanks and the commercial sector. Data users can browse data online and register with the Service to analyse and download them. Open Data collections are available for anyone to use.

The UK Data Service collection includes major UK government-sponsored surveys, cross-national surveys, longitudinal studies, UK census data, international aggregate, business data, and qualitative data. There are currently more than 6,000 datasets available from a variety of sources.

The Service offers training, resources and guidance to ensure that people are supported to make the best use of data in the collection. For data creators, the UK Data Service promotes good data management practices, from planning research through to the deposit of data in a repository.

To understand the diversity, complexity and types of e-infrastructures we conducted a secondary classification of infrastructures according to the following:

- E-infrastructure facilities (e.g. ARCHER, DiRAC)
- Experimental facilities, with a major requirement for e-infrastructure to support the research that facility users are carrying out (e.g. Diamond, SKA)
- 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 other classes of e-infrastructure above (e.g. Earlham Institute, HDR UK)

The majority of infrastructures fall into the category of institutes or centres with their own e-infrastructure (Figure 8.4).

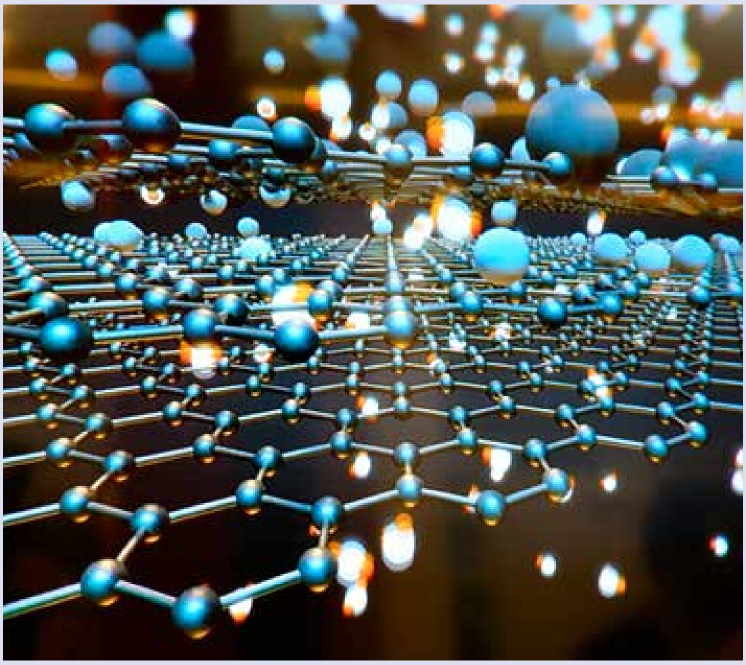
More E-infrastructures are physically located in the south of England than other regions (Figure 8.1). However, unlike sectors dominated by large, physical infrastructures that are visited in person, many E-infrastructures are accessed remotely over networks and from a user point of view their physical location is less important. Over half of the infrastructures in the sector are set up under virtual or hybrid models (Figure 8.1c). 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 may

The Materials and Molecular Modelling Hub (MMM) provides researchers carrying out research into materials, access to a state of the art HPC facility, named Thomas after Thomas Young.

Modelling and simulation enables 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, 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.



help explain why over a quarter are reliant on short-term funding (Figure 8.1d). However, many infrastructures in this sector do have a significant lifespan (Figure 8.1b). The classification presented in Figure 8.4 perhaps goes some way to explain these figures. The E-infrastructure itself may have a long lifespan, but the technology that it relies on will need regular replacement. For instance, Diamond Light Source 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[35]. From that questionnaire it was apparent that HEIs remain the main provider of data and compute services to the national e-infrastructure ecosystem with 36 HEIs providing national or regional services.

Links to the wider economy

Data is 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 the Hartree Centre is the only infrastructure directly targeted at industry, there is considerable industrial usage of other E-infrastructures either via academic/industrial collaborations as well as direct usage. Seventy-two percent of E-infrastructures stated that at least some of their work is informed by the needs of businesses (Figure 8.5). For example, ARCHER, the UK's National HPC Facility, collaborated with Rolls-Royce to demonstrate the scaling of modelling across many applications. However, most E-infrastructures generally support research at the discovery end of the spectrum (58%) or have a balanced portfolio (39%) (Figure 8.5).

The top economic sectors that e-infrastructures contribute to include research, communications, computing health services, pharmaceutical manufacturing, public policy and transportation (Table 8.2). What is not apparent from Table 8.2 is the depth and diversity of economic sectors that are supported by E-infrastructures. Each E-infrastructure supports an average of 17 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.

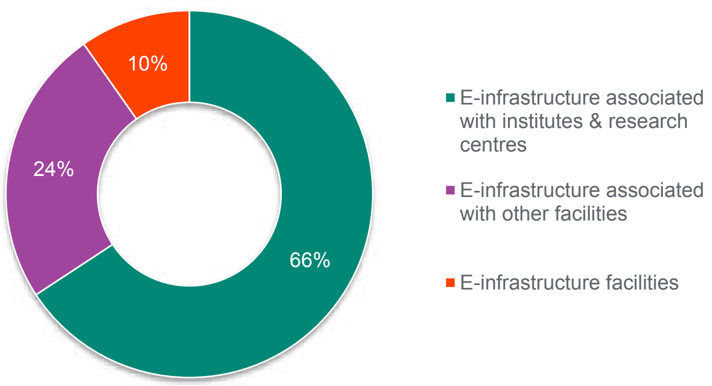


Figure 8.4. Types of e-infrastructures and data facilities.

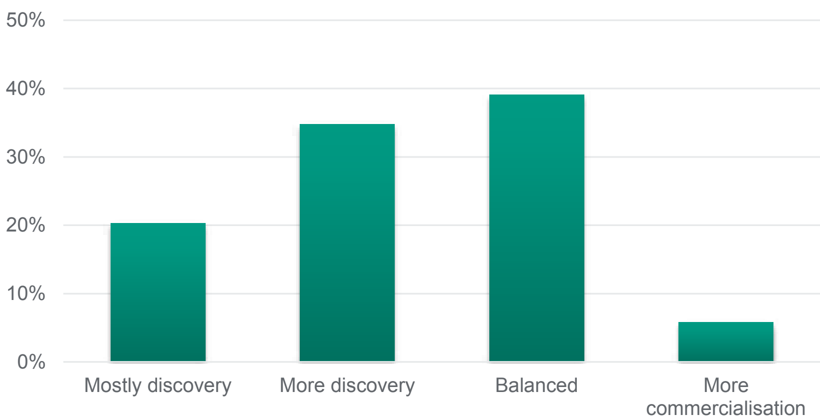
Rolls-Royce and the National Service

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 is a major player in the aeronautical sector with an annual spend of £800 million and a total impact of UK GDP of over £10.2 billion.

Scaling is important to Rolls-Royce to ensure they can meet their design timescales. 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 2-3 years.

Credit: Rolls Royce



66%

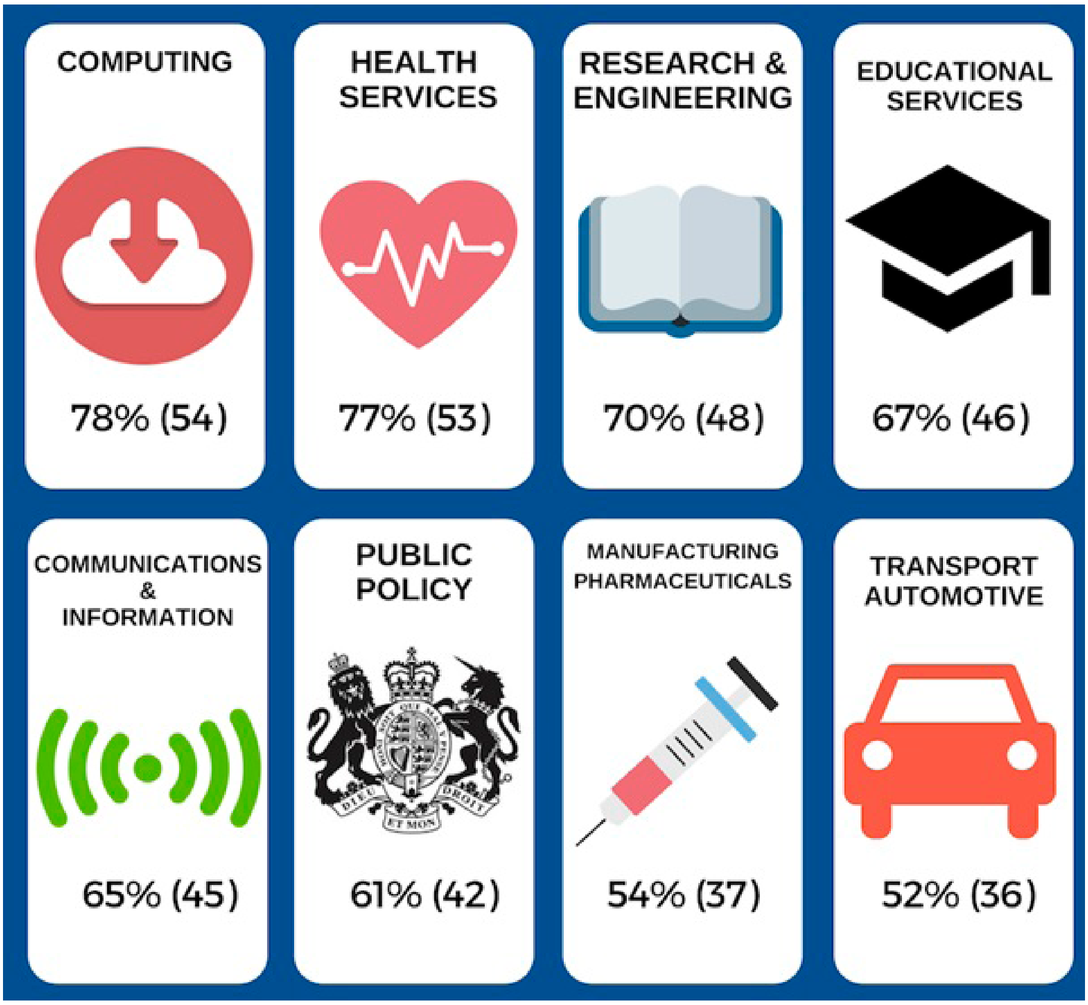
Work with non-academic public sector (>5% activity)

72%

Report at least some work is informed by businesses

Figure 8.5. The spread of E-infrastructures on a discovery to commercialisation spectrum.

Table 8.2. Top eight economic sectors that E-infrastructures work with.



Chapter 9: Next steps

This is the first time that an exercise of this breadth and type has been attempted in the UK. Whilst the questionnaire campaign had high uptake we recognise that it has not been possible to capture every infrastructure in every domain area during this phase.

One of the purposes of this initial landscape analysis is to further engage with the community to identify gaps in our knowledge of the research and innovation infrastructure landscape and improve our coverage, although we do not expect to achieve 100% coverage. We will re-release a questionnaire aimed at infrastructures who have not engaged with us previously during winter 2018-2019. The roadmap team is compiling a list of infrastructures to further interact with and information about such infrastructures should be communicated to **infrastructure@ukri.org**

Over the coming months we will continue to check and test the existing data and conduct further analysis not yet conducted or presented in this report. One aspect of this work will be to apply the organisational topology developed in Chapter 1 to the existing dataset to further understand the UK's landscape of infrastructures.
The final report of the landscape will be published alongside the final roadmap in spring 2019.

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[36] and H2020 Research Infrastructure Programme[37]:

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-site (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 will focus 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 out of scope
- Major research and innovation infrastructure 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 R&I organisation or part of an organisation.

The infrastructure should be regarded and operated as a strategic capability enabling collaboration, supporting provision 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 only to one or a very limited number of researcher or organisations
Publicly funded users may include HEIs, institutes, PSREs, RTOs and other R&I 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. user registration, fees, competition, merit review, conditions, security	

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.

- 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 HMG economic and societal challenges and priorities. Evidence of importance to user community through a range of pathways including 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 life-cycles) would not be within scope.

Annex B: Methodology

This initial analysis of the UK's current research and innovation infrastructures has drawn heavily from data collected through two questionnaires that reached over 800 existing infrastructures. This methodology annex first covers the content of the questionnaires, the approach taken to reach target respondents and response rates. 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. The annex concludes with a short discussion on filling gaps in the data set and implementing a classifications framework to support more robust analysis in the final report.

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

1. Questionnaire content

Broadly, the first questionnaire asked questions to gather a broad 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 table below 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 **Lifecycle stage:** • Stage of infrastructure in lifecycle • First year of operations • Lifespan **Domain/ sector:** • Research sectors covered • Primary research sector • Significance of e-infrastructure • Sectors of economy supported **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	**Legal nature:** • Legal nature of those infrastructures established as national legal entities **Domain/sector:** • Relevance of Roadmap sectors • Relevance of sub-disciplines within Roadmap sectors • Relevance of e-infrastructure (discipline of RII vs used as tool) • Expected growth of relevance of e-infrastructure **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 **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

Questionnaire one	Questionnaire two
Users: • How user numbers are measured • Number of users • Where users are from **Capacity:** • How capacity is measured • Percentage of capacity used • Target capacity use **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	**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 **Reviews and evaluations:** • Whether RII peer reviews users • Independent reviews of infrastructures **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 10 years • Expected growth of international users relative to national users

2. Target respondents and response rates

The target audience for the first questionnaire was all UK infrastructures and UKRI undertook extensive preparatory work to identify as many as possible and to establish contacts. A list of 697 infrastructures with contacts was developed in consultation with sector experts, government departments, the cross-government analyst network and the devolved administrations.

These infrastructures were personally invited to complete the first questionnaire. In parallel the questionnaire was promoted to all higher education institution vice chancellors by Research England and their devolved equivalents for wider coverage and to reach infrastructures with unknown contacts, plus hitherto unknown infrastructures. The link was also placed on the UKRI website and promoted by the National Academies, 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 43 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%.

3. 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 a infrastructure is recent and less embedded risking non-participation by 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 against these biases by cross-referencing our engagement against listings such as ESFRI[38] and MERIL[39].

There is not an even number of infrastructures in each of the six broad research sectors. Any overarching analyses of the landscape will be driven by sectors with the largest numbers of infrastructures (i.e. PS&E and BH&F) 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, on 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. Where known gaps exist these are described in sector chapters. Energy has a small number of infrastructures in the UK and received questionnaire returns from half of these. The questionnaire data has been supplemented with intelligence drawn from further consultations and workshops to overcome this limitation. Clinical infrastructures embedded in public health establishments whose primary purpose is treatment of patients but where high quality research and innovation may also be undertaken may also be under-represented. We aim to continue engagement in these areas and use the initial landscape report to identify others to improve our understanding for the final reports due in spring 2019.

Another source of potential bias arises from variation in infrastructures' scale and position in the organisational topology. In terms of scale there is equal weighting given to each infrastructure, for example whether it is the national archive (e.g. the British Library) or a smaller specialist one. Given that this report captures the entirety of the landscape it is unavoidable and if we were to attempt to weight infrastructures by size it would likely lead to new biases and complicate the issue further. We have engaged with a rich diversity of infrastructures in terms of their position within organisational topologies and have equally diverse questionnaire entries, from entire multi-tiered international infrastructures to partial infrastructures (e.g. national nodes of international infrastructures). One of the aims of presenting this initial landscape analysis is to test our proposed topology and our plan is to analyse entries according to their position for the final report in spring 2019.

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 the following criteria. Those failing any checks were not included in the analysis for this report (numbers indicate cases – note that some infrastructures failed on more than one criteria):

- Reliance on public funding (n=23)
- Accessibility to external users (n=13)
- Longevity (n=3)
- Capability and significance that is national or international (n=94, 43 of which were "local" and thus excluded from Sector analyses as well)

- Fits the description of a research and innovation infrastructure (n=11)
- Not duplicated (n=10)

During data exploration factual errors were corrected using information in explanatory fields or by further investigation, for example following misinterpretation of whether a funding source was public or private or to correct typing errors. We also included the option of adding a supplementary secondary classification to each infrastructure. This does not overwrite the original data but instead allows additional data exploration. An example of a supplementary secondary analysis in in Chapter 8 where computational and data infrastructures have been classified according to the facility type.

There were few patterns in the uptake rate of questionnaire two compared to questionnaire one. Response rates between sectors showed slight differences although uptake of questionnaire two exceeded 75% in each. There was no bias according to the lifecycle stage. infrastructures located outside the UK were more likely to complete questionnaire two than those located in the UK (94% versus 82%) as were those established as a legal entity compared with those housed within other institutions (89% versus 82%). There was no difference in uptake based on the organisational topology of the infrastructure (e.g. single site, grouped etc.). Overall uptake of questionnaire two by the 712 infrastructures on the national dataset was 83% which is exceptionally high for a questionnaire.

Areas for future development

It is hoped this initial analysis can serve as a useful prompt for community support in final gap filling within the data set. A final, targeted, data collection will take place before the final analysis and a list of infrastructures to contact is currently in development.

The issue of how entities have interpreted the definition of an infrastructure has meant the responses in the questionnaire data are not always ‘equal’ or comparable. For instance, some responses relate to a single facility whereas others are for institutions housing multiple facilities. To manage the different scales of response, a classification framework is being developed and all responses in the data set will be classified ahead of the final analysis. This will allow the separation of ‘apples and oranges’ and permit more controlled analysis. The classification exercise may also help identify gaps and feed into preparations for the final report.

Acronyms

AFRC	Advanced Forming Research Centre
AI	Artificial Intelligence
AIRTO	Association for Innovation, Research and Technology Organisations
ALSPAC	Avon Longitudinal Study of Parents and Children
AMRC	Advanced Manufacturing Research Centre
ARCHER	Advanced Research Computing High End Resource
BAME	Black, Asian and Minority Ethnic backgrounds
BBSRC	Biotechnology and Biological Sciences Research Council
BSC70	1971 British Cohort Study
BEIS	Department for Business, Energy and Industrial Strategy
BH&F	Biological Sciences, Health and Food
BHPS	British Household Panel Survey
CERN	Conseil Européen pour la Recherché Nucléaire (European Organization for Nuclear Research)
CESI	Centre for Energy Systems Integration
CESSDA	Consortium of European Social Science Data Archives
CLF	Central Laser Facility
CLOSER	The Cohort and Longitudinal Studies Enhancement Resource
CPI	Centre for Process Innovation
DCMS	Department for Digital, Culture, Media & Sport
DWP	Department for Work and Pensions
E-INF	E-infrastructure
EBI	European Bioinformatics Institute
ECCI	Edinburgh Centre for Carbon Innovation
EEA	European Economic Area
EEG	Electroencephalography
EISCAT	European Incoherent Scatter Scientific Association
ELIXIR	European Life Science Infrastructure for Biological Information
EM	Electron Microscopy
EMBL-EBI	European Molecular Biology Laboratory - European Bioinformatics Institute
ENV	Environmental Sciences
EOSC	European Open Science Cloud
EPOS	European Plate Observing System
EPR	Electron Paramagnetic Resonance
EPSRC	Engineering and Physical Sciences Research Council
Ergo	East Riding of Yorkshire Council
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EU	European Union
EuroHPC	European High-Perfomance Computing
FAAM	Facility for Airborne Atmospheric Measurements
FTE	Full Time Equivalent
GDP	Gross Domestic Product
HDR UK	Health Data Research UK
HEI	Higher Education Institution
HESA	Higher Education Statistics Agency
HMG	Her Majesty’s Government
HND	Higher National Diploma
HPC	High Performance Computing
ICT	Information and Communications Technology
ISIS	ISIS Neutron and Muon Source
JASMIN	Joint Analysis System Meeting Infrastructure Needs
JET	Joint European Torus
LIGO	Laser Interferometer Gravitational-Wave Observatory
MAST	Mega Amp Spherical Tokamak
MCS	Millennium Cohort Study
MERIL	Mapping of the European Research Infrastructure Landscape
MMM	Materials and Molecular Modelling Hub
MONSooN & Monsoon2	Met Office and NERC Supercomputing Node
MRC	Medical Research Council
MRF	Materials Research Facility
MTC	Manufacturing Technology Centre
NARF	National Avian Research Facility
NCC	National Composites Centre
NCDS	1958 National Child Development Study
NERC	Natural Environment Research Council
NGR	National Geological Repository
NHS	National Health Service
NIH	National Institutes of Health
NLSY	National Longitudinal Survey of Youth
NMR	Nuclear Magnetic Resonance
NNL	National Nuclear Laboratory
NPL	National Physical Laboratory
NWTF	National Wind Tunnel Facility
PACT	Pilot-scale Advanced Capture Technology
PRL	Pyrochemical Reprocessing Laboratory
PS&E	Physical Sciences and Engineering

PSRE	Public Sector Research Establishments
QR	Quality Related block funding to UK HEIs
R&D	Research and Development
R&I	Research and Innovation
RACE	Remote Application in Challenging Environment
RAL	Rutherford Appleton Laboratory
RFI	Rosalind Franklin Institute
RRS	Royal Research Ship
SAPO	Specified Animal Pathogens Order
SFC	Scottish Funding Council
SKA	Square Kilometre Array
SME	Small and Medium-sized Enterprises
SPECIFIC	The Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings
SSAH	Social Sciences, Arts and Humanities
STFC	Science and Technology Facilities Council
UBDC	Urban Big Data Centre
UCB	Union Chimique Belge
UKAEA	UK Atomic Energy Authority
UKCRIC	UK Collaboratorium for Research Infrastructure and Cities
UKDS	UK Data Service
UKRI	United Kingdom Research and Innovation
UKSA	UK Space Agency
WMG	Warwick Manufacturing Group
XFEL	X-ray Free Electron Laser

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References

1 UK Research and Innovation, **UKRI strategic prospectus** (2018)
2 UK Research and Innovation Infrastructure Roadmap Programme, progress report **https://www.ukri.org/research/infrastructure/**
3 European Commission, **About Research Infrastructures**
4 Department for Business, Innovation & Skills, **BIS' innovation infrastructure – working towards an innovation system** (2010)
5 Department for Business, Innovation and Skills, **Innovation Report 2014: innovation, research and growth** (2014)
6 Department for Business, Innovation & Skills, **Research and Innovation Organisations in the UK: Innovation Functions and Policy Issues, BIS research paper number 226** (2015)
7 Independent, **Numbers studying physics rise as blockbuster films, the Hadron Collider and the Mar Rover inspire students** (2015)
8 ESFRI Scripta. I**nnovation-oriented cooperation of Research Infrastructures** (Vol 3, 2018)
9 Europa, **Group of Senior Officials on Global Research Infrastructure Progress Report** (2015)
10 ESFRI, **Home page**
11 Europa, GSO Progress Report **https://ec.europa.eu/research/infrastructures/pdf/gso_progress_report_2017.pdf#view=fit&pagemode=none** (2017)
12 ESFRI, **ESFRI Roadmap** (2018)
13 Technopolis, Science Research Investment Fund: a review of Round 2 and wider benefits (2009)
14 Research England, Research and knowledge exchange funding for 2018-19: Recurrent grants and formula capital allocations (2018)
15 Technopolis, **Hartree Centre Phase 1&2 Baseline Evaluation** (2018)
16 Office for National Statistics, **UK SIC 2007**
17 Catapult Network, **Fostering Innovation to Drive Economic Growth** (2017)
18 HESA, 2017 **Staff data**
19 National Institute for Health Research, **NIHR infrastructure**
20 AMRC, **Charities' Funding Contribute to UK Medical Research Excellence** (2017)
21 European Strategy Forum on Research Infrastructures, **Roadmap 2018: Strategy Report on Research Infrastructures** (2018)
22 The Royal Society, **A snapshot of UK research infrastructures** (2018)
23 Biobank, **Home page**
24 Medical Research Council, **Clinical Research Capabilities and Technologies Initiative**
25 The Frank Crick Institute, **Worldwide Influenza Centre**
26 Instruct ERIC, **Instruct Centre UK**
27 **http://www.ukbiobank.ac.uk/**
28 **https://allofus.nih.gov/**
29 Smith, SM. Genome-wide association studies of brain imaging phenotypes in UK Biobank. *Nature* 2018 Oct; **562**(7726):210-216. doi: 10.1038/s41586-018-0571-7
30 Caulfield, MJ. Genetic analysis of over 1 million people identifies 535 new loci associated with blood pressure traits. *Nat Genet*. 2018 Oct;**50**(10):1412-1425. doi: 10.1038/s41588-018-0205-x
31 Economic & Social Research Council, **Longitudinal Studies Review 2017** (2018)
32 **http://www.cms-lawnow.com/ealerts/2001/03/the-green-paper-work-and-parents-competitiveness-and-choice?cc_lang=en**
33 **https://revenuebenefits.org.uk/pdf/savings_and_assets_for_all.pdf**
34 Urban Big Data Centre, **Strava Metro Data**
35 National E-infrastructure Report, h**ttps://hpc-sig.org.uk/index.php/publications/2017-national-e-infrastructure-report/** 2017
36 ESFRI Glossary **https://www.esfri.eu/glossary**
37 European Commission: About Research Infrastructures, **https://ec.europa.eu/research/infrastructures/index.cfm?pg=about**
38 European Strategy Forum on Research Infrastructures, **Projects and Landmarks (2018)**
39 Mapping of the European Research Infrastructure Landscape (MERIL), **Home page**

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