technopolis group

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# Impact evaluation of ESRF

**Final Report**

Version 2

*March 2023*

# Impact evaluation of ESRF

## Final Report

Neil Brown, Vivek Seth, Nadya Mihaylova, Charlotte Glass, António Neto, Aaron Vinnik, Julie D'Hont, Adebisi Adewusi, Tia J'Nae Murray, and Reda Nausedaite

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# 1 Executive summary

The European Synchrotron Radiation Facility (ESRF) at Grenoble is the world's brightest X-ray light source, providing X-rays that are 100 billion times brighter than those used in hospitals. This enables users to study the position and motion of atoms, helping them explore materials and living matter in fields as diverse as chemistry, material physics, biology and medicine, and cultural heritage. ESRF's upgrade to the Extremely Brilliant Source (EBS) in 2020 provides users with the world's first fourth-generation high-energy synchrotron.

The UK joined the ESRF as founding member in 1988. STFC currently contributes c.10.5% (c. €9.5 million) annually to the facility's budget to secure access for UK users and suppliers. EPSRC also funds ESRF's XMaS beamline (c. €1.7 million per year), which then prioritises beamline time for UK researchers.

STFC appointed Technopolis to undertake an evaluation that would measure and demonstrate the impacts from the UK's involvement in ESRF during the period 2011-2020. The study found that the UK's shareholding in and access to ESRF has given the country substantial benefits in a variety of areas, which are summarised below.

## 1.1 Unique capabilities enabling high-volume, high-quality UK science

- The UK is one of ESRF's heaviest users with approximately 370 different users each year.
- Over the last decade, UK users have published 3,300 research publications linked to ESRF. This represents 17% of all publications linked to ESRF, higher than the UK's shareholding
- UK scientists have used ESRF's unique capabilities to deliver cutting-edge research, from innovative 3D imaging to study the effects of Covid-19 on the human lung, to helping to conserve the Mary Rose Tudor warship
- ESRF's capabilities complement those of the UK's national synchrotron facility, Diamond Light Source (Diamond), with many researchers making use of both facilities. ESRF excels for very high energy photons, while Diamond is world-class for lower energy beamlines.
- The majority of user survey respondents indicated that without ESRF, many of their projects would simply have not been possible.

## 1.2 Supporting diverse and multidisciplinary UK science

- While the research conducted at ESRF is predominantly pure science, UK users have also conducted significant applied research, including IONTAS' work on COVID-19 antibodies, and GSK's research into toothpaste formulation
- ESRF supports a diverse range of disciplines in the UK, across UKRI's remit. It has transitioned from primarily being used by physicists, to becoming increasingly important for other areas including the life sciences, chemistry, and cultural heritage
- 80% of publications by UK users have been multi-or interdisciplinary, approximately double the value seen across all published academic papers

## 1.3 Improving research skills and training the next generation of scientists

- ESRF access has created strong skills benefits for UK researchers, notably improving their ability to work in international environments and international teams.
- ESRF has been particularly important in training early career researchers, and 85% of user survey respondents indicated that ESRF was essential to training the next generation of scientists
- The XMaS Scientist Experience has encouraged female Year 12 physics and STEM students to consider science-based careers by funding educational trips to ESRF

## 1.4 Supporting the UK research and innovation community

- ESRF involvement and engagement has had spillover benefits for UK research facilities, including at Diamond, providing them with technologies, best practice and trained staff
- ESRF engagement protects the UK research community's access to leading research facilities, especially when UK-based facilities are unavailable (e.g. during the forthcoming Diamond upgrade) or are in high demand.
- ESRF helps STFC and UKRI meet its strategic goals to strengthen the UK's research and innovation community, in relation to early career researchers, and access to international networks and opportunities

## 1.5 Contributing to UK government priorities

- The UK's interactions with ESRF have contributed towards wider government policy priorities including:
  - technologies that will help decarbonise the economy (e.g. improving lithium-ion batteries and hydrogen fuel cells)
  - supporting businesses (especially suppliers to ESRF) based outside the south-east, helping with levelling up
  - supporting SME growth through supplier contract opportunities
  - helping fulfil UK aims to become a science superpower by 2030, by enabling cutting-edge UK-led research
  - improving healthcare (e.g. work looking at treatments for COVID-19 and Alzheimer's)

## 1.6 Enhancing the UK's international standing

- Involvement in ESRF has increased international collaboration opportunities, with the share of UK-authored publications citing ESRF that involved no international partners falling from 25% in 2011 to 8% in 2021
- The UK benefits from soft power gains, maintaining influence in international science decision making through its involvement in ESRF

## 1.7 UK businesses winning contracts

- Nearly €16 million of contracts were won by UK suppliers to ESRF between 2015 and 2021
- The UK has sold a range of different goods and services to ESRF, including magnets, software and control systems, and instruments. The UK's supplier base is diverse, encompassing the public sector, engineering and manufacturing firms, and software firms
- These contracts have given UK suppliers the skills and market visibility to gain work elsewhere, including at other high-profile research facilities both in the UK and world-wide

## 1.8 UK industrial innovation and creating jobs

- Approximately 5% of the facility's UK users have been from industry (e.g. pharmaceuticals, public energy, and engineering firms), using ESRF to undertake fundamental research that will help develop new products and services
- ESRF has played an important role in helping create and retain high value-added jobs. UK users reported that the ability to work on high-profile and cutting-edge projects has helped attract and retain skilled researchers and engineers to the UK
- A notable example of a UK university spinout forming from research undertaken at ESRF is Finden, a UCL spin-out providing measurement services, which now employs ten people.

# European Synchrotron Radiation Facility (ESRF)

**372**
unique UK users
Per year

**44** Beamlines
(currently)

**Supports UK users across diverse disciplines including:**
Chemistry
Physics and Engineering
Medicine
Cultural Heritage

**4,367**
UK user *visits*
between 2011-2018

**UK is the 4th largest contributor and user**
covering 10% of ESRF costs and accounting for 9% of users

## ESRF supports High Quality Research

Critical to research

81%

ESRF access has significant impact on ability to pursue particular research questions

**3,300**
articles published
(2011-2021)

UK accounted for
**17%**
of ESRF related publications in refereed journals
(2011-2021)

**80% of papers were inter or multidisciplinary**
2.6 research areas per paper (2021)
(on average)

## ESRF supports Skills and Knowledge

**91%**
**indicated the great importance of ESRF on research skills development**

**Each year ESRF hosts**
High Schoolers
Undergraduates
PhD students
Visiting researchers

**85%**
**ESRF essential to training the next generation of scientists**

**99%**
**of people surveyed said**
**YES**
**ESRF has led to important advances in knowledge**

## Wider UK Policy & Strategic Objectives

**STFC**

- Meets strategic goal to strengthen the UK research and innovation community
- Critical to attract skilled scientists and engineers to the UK
- Spillover benefits to Diamond Light Source and other facilities through experience, technology and best practice

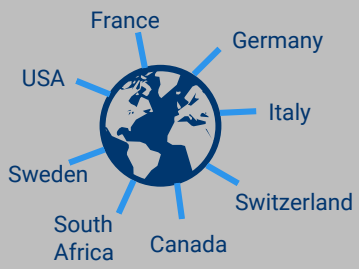
**Wider UK**

- Supports decarbonising/net-zero technologies
- Levelling up - supporting businesses outside the south-east
- Helps fulfil aim of becoming science superpower by 2030
- Supports SME growth through supplier contracts

## ESRF supports International Collaboration

**92%**
of papers in 2021 included an international partner

**Most Common Collaborators**




## ESRF supports Suppliers

**£16m in contracts between 2015-2021**

**UK accounts for 6% of total ESRF contracts between 2015 and 2021**

**ESRF contracts have helped establish specialist businesses in the UK**

# 2 Introduction

This report presents the impact evaluation of the UK's involvement in the European Synchrotron Radiation Facility (ESRF) and an evaluation framework for future monitoring.

## 2.1 The European Synchrotron Radiation Facility (ESRF)

**STFC** provides UK researchers with access to world-class research facilities. It manages and funds several major research infrastructures within the UK itself, including the Diamond Light Source synchrotron at Harwell, the Central Laser Facility at the Rutherford Appleton Laboratory, and the e-Merlin radio astronomy facility at Jodrell Bank. Alongside these UK-based facilities, STFC also manages access for UK researchers to international science facilities, including the European Synchrotron Radiation Facility (ESRF), which is the focus of this report.

**ESRF** is a synchrotron based at Grenoble, France. It was initiated in 1988, with user operations beginning in 1994. In 2018, it was then shut down for a 20-month upgrade to a new Extremely Bright Source (EBS). ESRF provides the most intense source of synchrotron-generated light in the world, with X-rays that are 100 billion times brighter than those used in hospitals. This enables users to study the position and motion of atoms, helping them to explore materials and living matter in fields as diverse as chemistry, material physics, biology and medicine, and cultural heritage.

Demand for access to ESRF's 44 beamlines is high, with the facility attracting close to 9,000 scientists a year. Most of the beamlines are accessed through a peer review process controlled by the facility itself. However, thirteen of the beamlines are designed, constructed and operated by collaborating research groups (CRGs). While these CRGs can prioritise access to their beamlines for their own members, they must still reserve a third of beamline time for access secured via the independent peer review process that non-CRG beamlines use.

**The UK** joined ESRF as a founding member in 1988. STFC now contributes approximately 10.5% (c.€9.5 million)[1] of ESRF's annual budget, making the UK the fourth biggest financial contributor. This financial contribution provides access to the facility for UK researchers; scientists from non-member countries can only obtain beamtime in collaboration with users from member countries or a very limited quota of beamtime granted by ESRF management. Users from member states still need to apply via the peer review process, so UK usage on a par with the UK shareholding is not guaranteed and will depend on the quality of UK proposals and the level of competition from other countries. Prior to the upgrade of the facility, there were approximately 400 UK users of ESRF each year, with the proportion of beamtime used by UK researchers being broadly in line with its percentage financial contribution to the facility. The UK has also formed a CRG which — via the Engineering and Physical Sciences Research Council (EPSRC) — has operated the XMaS (X-ray Magnetic Scattering) beamline at ESRF since 1997.

Much of the research conducted at ESRF might be classified as fundamental or pure science. However, UK users have also conducted more applied research at the facility. Examples include IONTAS' work on COVID-19 antibodies, GSK's research into toothpaste formulation, and the University of Manchester and Rolls-Royce's study into micro-cracks in composites.

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/460406/EM_Prot_Russ.pdf (accessed 6 September 2022)

## 2.2 Impact evaluation of the UK's involvement in ESRF

STFC appointed Technopolis to carry out an impact evaluation study of the benefits from the UK's investment and partnership in ESRF (2011-2020). There are a wide variety of impact types that we might expect the facility to produce, and therefore a range of different areas in which the UK may benefit from its shareholding and access. These include:

- **Scientific and research benefits:** including the role that ESRF plays in advancing academic and commercial research, including through multidisciplinary and interdisciplinary research
- **Skills benefits:** including R&D skills amongst users and suppliers, as well as impacts on apprentices and students
- **UK policy and wider strategic objectives:** including meeting goals in STFC's Delivery Plan, and other wider government policy objectives
- **UK's international standing:** including the UK's ability to influence international science, and ESRF's role in enhancing the UK's reputation as a centre of world-leading science
- **UK benefits from supplying the facilities:** including the additional revenue gained by firms from facility contracts, and benefits to their supply chains
- **Commercial and economic benefits:** including the sale of products based on research at ESRF, or the production of spinouts from university research based at the facility

In Part 1 of this report we present the findings of our impact evaluation, examining each of the above impact pathways in turn. Part 2 then sets out an evaluation framework that STFC can use to monitor impacts in each of these pathways going forward.

A parallel study looking at the impact of the UK's involvement in European XFEL was also undertaken. The two studies are underpinned by a common workplan, consultees and underlying assumptions. A joint methodology report is therefore provided separately.

# Part 1: Impact Report

# 3 Scientific and research impacts

ESRF's most notable impact on the UK has been in advancing scientific research led by UK-based researchers. This section sets out evidence on the different ways that UK researchers have used the facility, the types of research that have benefited from the facility, and the specific ways that ESRF has helped advance research.

## 3.1 Summary

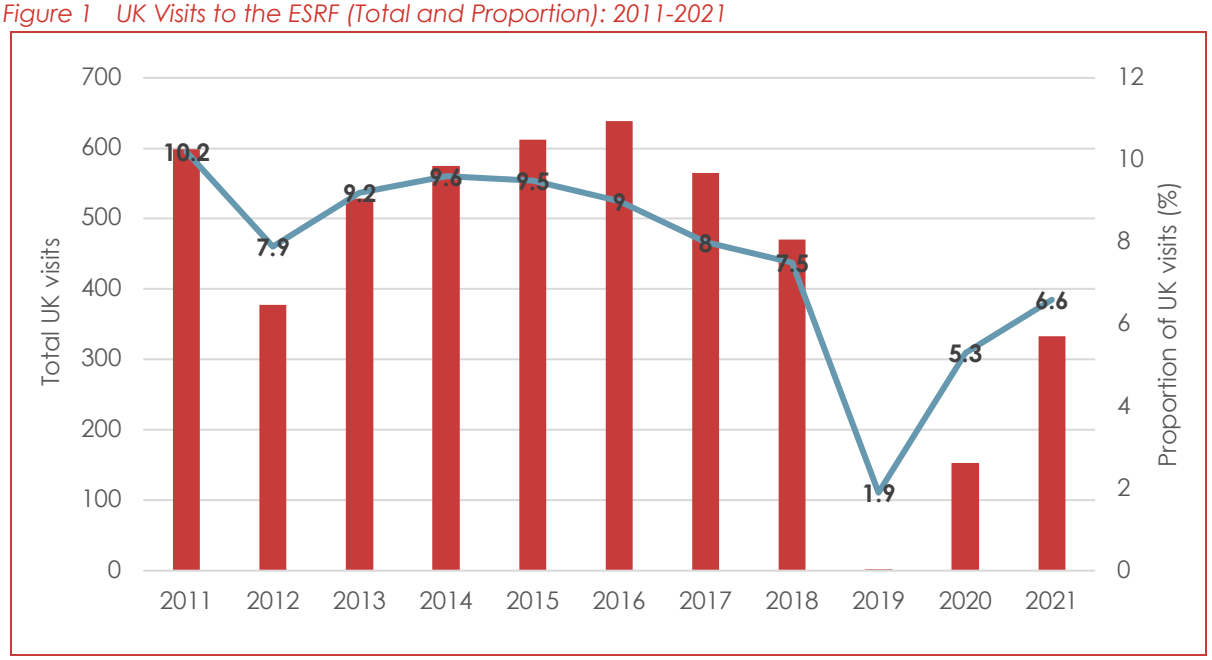
- The UK's usage of ESRF has been in line with its shareholding. It is one of the facility's heaviest users, with only three other countries (all of whom have higher shareholdings) having used it more over the last ten years
- ESRF supports a diverse range of disciplines for the UK. Having previously been used primarily by physicists, the facility has become increasingly important for UK users in other diverse research areas including life sciences, chemistry, and cultural heritage
- The UK's share of research publications linked to ESRF usage is also higher than its shareholding, indicating that ESRF has supported high quality research for UK researchers
- The majority of UK research publications that have cited ESRF have been multi or interdisciplinary. Levels of multidisciplinary research at ESRF also seem to be higher than average.
- ESRF access has also provided wider benefits to research teams, such as improved reputations, improved understanding of research areas, and improved international networks
- ESRF has offered high additionality, offering capabilities that are not available elsewhere. It has therefore supported research that might not be possible otherwise.

## 3.2 Scale of ESRF usage

Figure 1 shows the total number of UK visits[2] made to ESRF between 2011 and 2020 (the study period). The figures for 2019 to 2021 are anomalous, owing first to the ESRF shutdown and then the COVID-19 pandemic (which restricted in-person usage of the facility). Before this, the UK accounted for 4,367 visits between 2011 and 2018, reaching a peak of 639 visits in 2016. Over this period, the UK accounted for approximately 9% of all visits to the facility, which is broadly in line with the UK's 10.5% shareholding in ESRF.

[2] The total number of times that researchers have used ESRF in person. In other words, if a single researcher used ESRF three times in a year, this counts as three visits.

*Figure 1 UK Visits to the ESRF (Total and Proportion): 2011-2021*

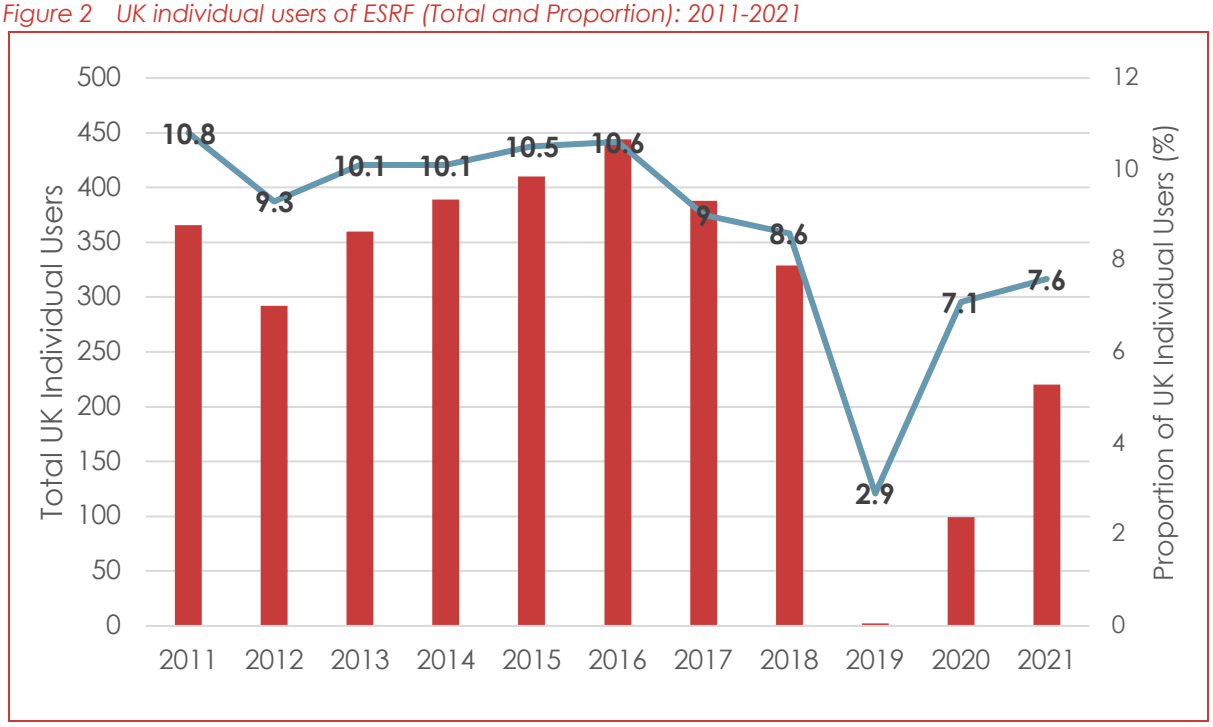



Source: ESRF DG monitoring data

The trends for the number of individual UK users (Figure 2) mirror that of total visits. Between 2011 and 2018, the UK saw on average 372 unique users each year, peaking in 2016. It accounted for around 10% of ESRF visitors each year, which is in line with the UK's 10.5% facility shareholding.

The number of UK users is lower than the number of UK visits, as a single user can make multiple visits in a year. However, the data does suggest that the UK tends to account for a higher proportion of all users than it does of all visits (suggesting use occurs across a broader base of researchers for the UK than in some other countries).

*Figure 2 UK individual users of ESRF (Total and Proportion): 2011-2021*




Source: ESRF DG data provided to STFC, March 2022

The fact that the UK's usage of ESRF is broadly in line with its shareholding demonstrates that the country is making full use of its investment – overuse of the facility would incur additional costs for the UK. Indeed, when compared to other countries, the UK is one of the facility's heaviest users. Only three other countries accounted for a higher proportion of total beamtime during the period 2011 to 2021: Germany (25%), France (24%), and Italy (12%), relative to the UK's 9%.[3] All three countries have larger shareholdings in ESRF than the UK, so would reasonably be expected to be heavier users.

## 3.3 Disciplines that have benefited from ESRF

The UK's ESRF user community is diverse, demonstrated by the range of research councils that have supported research at the facility. According to Researchfish data, there have been 376 awards made by UK Councils for work at ESRF, including research grants, studentships and fellowships. Approximately half of these (98, 51%) have been awarded by the Engineering and Physical Sciences Research Council (EPSRC). However, a quarter (26%) have come from the Medical Research Council (MRC), and 16% (61) from the Biotechnology and Biological Sciences Research Council (BBSRC). Other bodies, including the Natural Environment Research Council (NERC) and the UKRI-funded Faraday Institution have also awarded funding to research projects based at ESRF. This shows the breadth of the scientific and engineering communities that have an interest in using the facility.

Stakeholders have explained that while physicists, specifically those studying magnetism, have historically been the facility's keenest users, the UK has been present in every area of science and over the last ten years the UK ESRF user community has evolved to become very diverse.

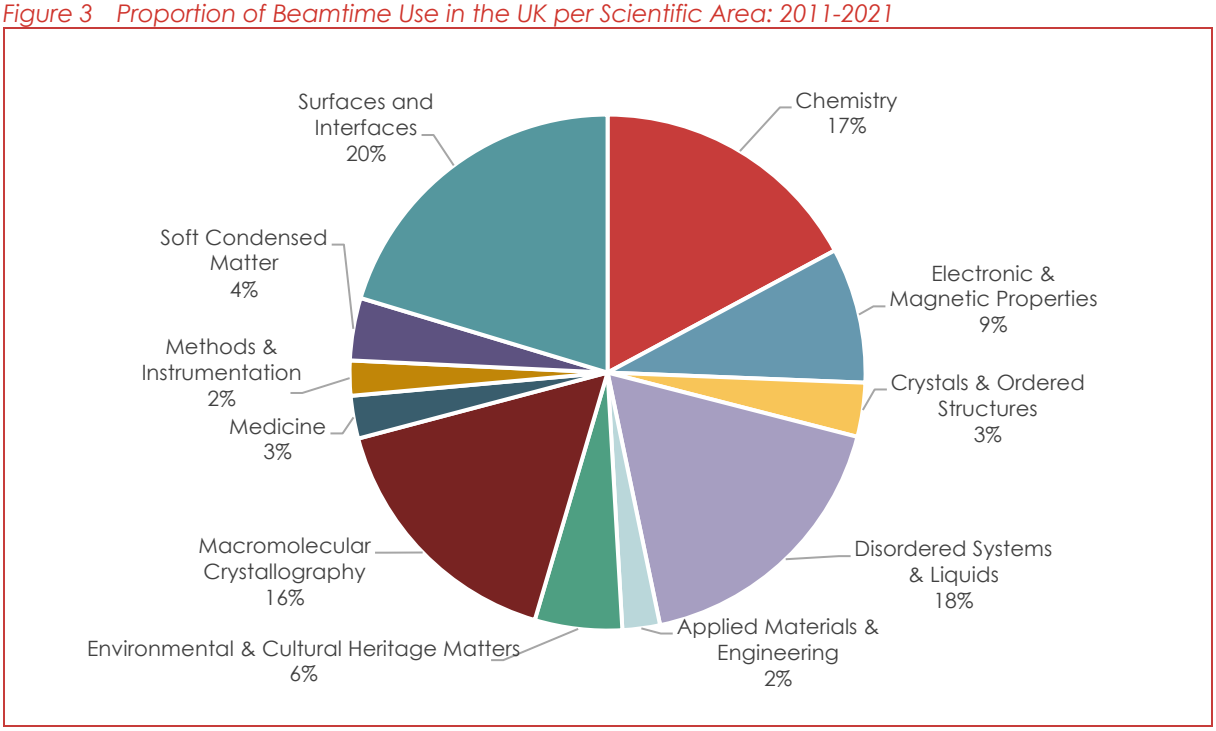
There has been particular growth in the number of chemists using the facility, as well as greater interest from UK scientists studying electron chemistry and polymers. ESRF monitoring data also shows growth in beamline usage by UK researchers (2011-2021) in the field of methods and instrumentation (from 5.52 to 39.98 shifts, a 624% increase) and disordered systems and liquids (from 26.25 to 158.30 shifts, a 503% increase)[4]. Structural biology has also become a major driver of ESRF demand, both amongst UK users and beyond, with pharmaceutical companies, for example, tending to use ESRF to help in the early stages of research. Stakeholders also spoke of how the UK has been particularly active in engineering and cultural heritage too.

Figure 3 emphasises the diversity in the research disciplines of UK ESRF users throughout the study period. A majority of UK beamtime use between 2011- 2021 has been in the following scientific areas: surfaces and interfaces (20%), disordered systems & liquids (18%), chemistry (17%), and macromolecular crystallography (16%). However, there is also notable UK usage in areas such as electronic & magnetic properties, and environmental & cultural heritage.

[3] ESRF monitoring data

[4] Over the same period some other fields have decreased their usage. In particular, crystals and ordered structures (from 141.22 to 4.69 shifts, a 97% decrease) and soft condensed matter (from 131.67 to 12.8 shifts, a 90% decrease).

*Figure 3 Proportion of Beamtime Use in the UK per Scientific Area: 2011-2021*




Source: ESRF monitoring data

The data above highlights ESRF's importance to UK researchers not only within traditional physics communities, but also more widely, including subject matters traditionally associated with the arts and humanities. For example, a UK-led research team used ESRF X-ray techniques to map harmful deposits sprayed onto the wood of the famous Mary Rose warship in 1982 as part of its preservation. The ability to track this polymer over time will make a vital contribution to the conservation of this priceless Tudor artefact.[5]

Through its involvement in the XMaS CRG beamline, the UK has been able to further support materials science research. The beamline had tended to focus more on nuclear isotopes and large elements. However, being situated on a bending magnet at ESRF, XMaS also provides a unique combination of instrumentation for high resolution and (magnetic) single crystal diffraction.[6] Over time, the applied materials science research community recognised the benefits that this combination of instrumentation and light penetration at XMaS could provide.

Stakeholders highlighted the growth in applied materials science research at XMaS, including the stress testing of industrial materials, and work centred on the development of new pieces of equipment. Indeed, some consultees estimated that commercial research now accounted for approximately 10% of all research taking place at XMaS. Once again, XMaS is typical of a broader trend seen across the entirety of UK usage of ESRF, of research communities becoming much more varied and diverse.

## 3.4 Supporting research that could not occur elsewhere

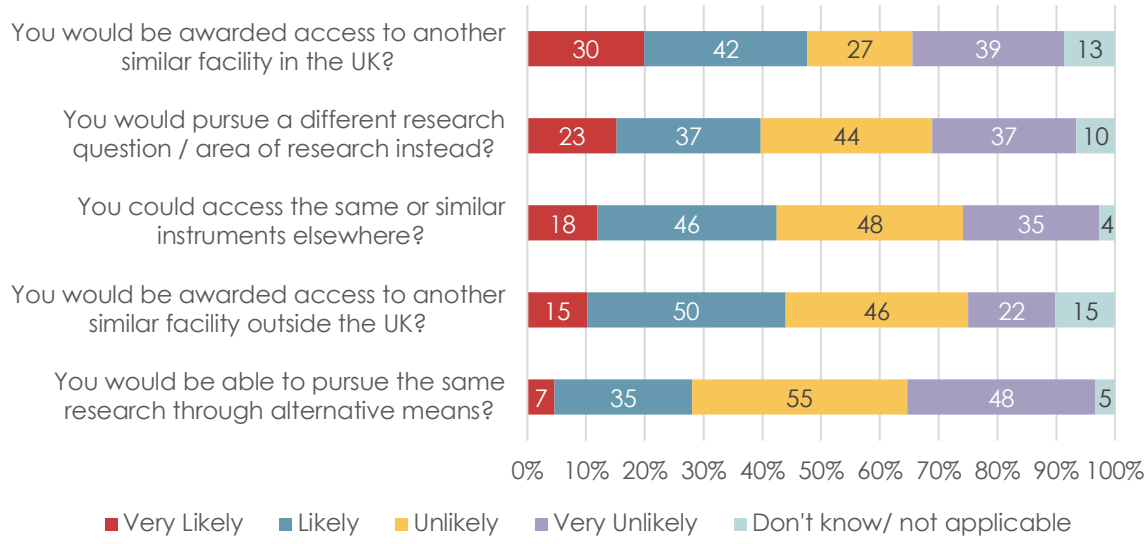
Almost 70% of survey respondents (UK users of ESRF) believed that they would not have been able (unlikely or very unlikely) to pursue the same research through alternative means without

[5] ESRF (2021) *The ESRF gives conservation boost to a 500-year-old shipwreck* (Internet). Available at https://www.esrf.fr/home/news/general/content-news/general/the-esrf-gives-conservation-boost-to-a-500-year-old-shipwreck.html

[6] https://www.esrf.fr/UsersAndScience/Experiments/CRG/BM28 (accessed 7 September 2022)

ESRF access. Also, around 55% said it was "unlikely" or "very unlikely" that they could have accessed the same or similar instruments elsewhere (either in the UK or beyond), or that they would be awarded access to another similar facility outside the UK. This highlights the importance of ESRF as a vehicle to ensure that researchers have the necessary support to conduct their scientific work.

*Figure 4 User survey responses to "If the UK were not a member of ESRF, how likely is it that..."*




Source: ESRF user survey (n=152)

Interview evidence also highlighted the centrality of ESRF to many UK-based researchers, particularly in being able to support research that would not be as easily replicated elsewhere. ESRF's recent upgrade to the Extremely Bright Source (EBS) means that the facility can produce X-ray beams with a brilliance and coherence that is 100 times greater than other present-day light sources. This increased performance opens new areas of fundamental research at atomic and macromolecular levels, both of materials and living matter.

Since 2020, ESRF has been the world's only fourth generation synchrotron, with beamlines going far deeper into a sample than at other similar facilities.[7] ESRF therefore offers greater capability than other synchrotrons that UK researchers commonly access, including the UK-based Diamond Light Source facility. Specifically, ESRF excels for the very high energy photons, while Diamond remains world-class for lower energy beamlines.[8] To that end, stakeholders have commented on how, while Diamond's beamlines are very well matched to the needs of UK users and can cater for a high volume of UK research, there are more specialised needs that only ESRF can meet. This aligns with STFC's own assessment of the UK's light sources.[9]

While there are a handful of other synchrotrons around the world that have similar capabilities to ESRF (e.g. Brookhaven's National Synchrotron Light Source), the fact that the UK has no shareholding in these facilities makes it more difficult to secure beamtime there. ESRF also provides a geographically proximate facility, which helps to reduce the time and resource

[7] https://www.esrf.fr/home/UsersAndScience/Accelerators/ebs---extremely-brilliant-source.html (accessed 3 November 2022)

[8] STFC (2021) *A Strategic Vision for the UK's Large-Scale Light Source User Facilities,* p. 17

[9] Ibid, p.15.

costs of research activity. In this way, ESRF has helped support UK science that would not only be impossible for technical reasons at Diamond, but would also be difficult or impractical to undertake elsewhere.

Even prior to its upgrade, ESRF was regarded as being one of the world's leading synchrotrons, described in STFC's 2016-2020 Delivery Plan as being one of the "world-leading international research facilities."[10] The Delivery Plan stressed the need to maintain access to both ESRF and Diamond – part of a broader commitment to "properly support…science exploitation of all the national and international mission-based facilities and experiments."[11] STFC recognised that maintaining access to this international facility as well as the national ones was vital in ensuring that UK researchers had access to the suite of capabilities needed to produce world-leading research.

## 3.5 ESRF supporting high quality research

With journal articles having to go through peer review to enable publication, having a published journal article often indicates the presence of high-quality research. Between 2011 and 2021, there have been over 3,300 published papers involving a UK author which have cited usage of ESRF. Throughout this period, UK authors have consistently accounted for approximately 17% of ESRF publications in reviewed journals in any given year. Comparing this figure to the UK's 10.5% shareholding suggests that the UK has fared better than other countries in supporting high quality research through ESRF.

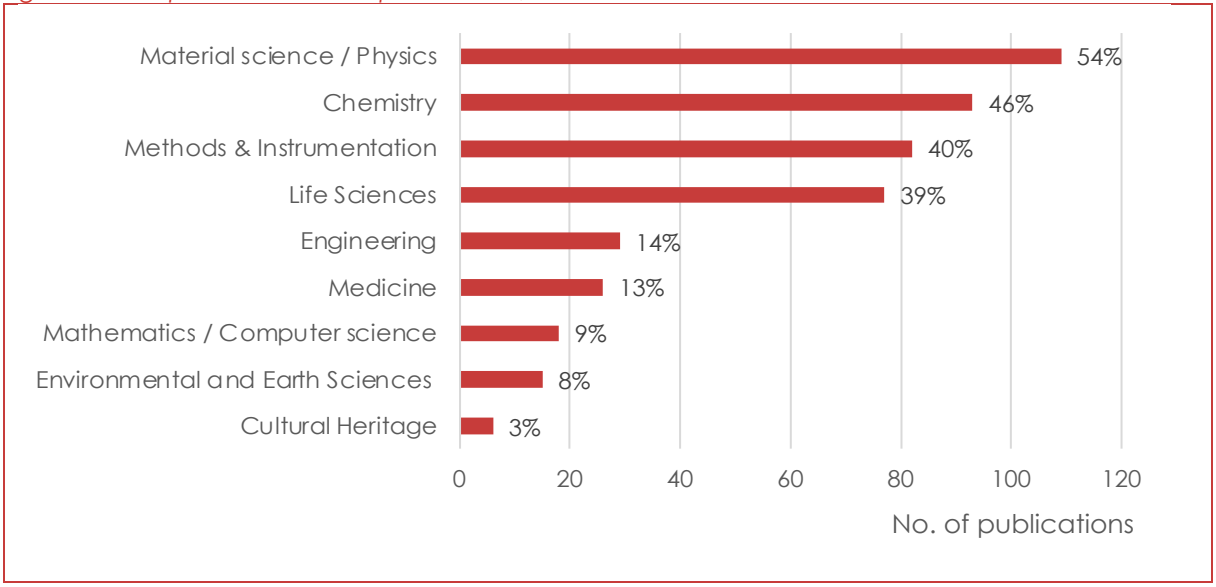
As shown in Figure 5, it is also clear that ESRF has enabled UK research publications for a wide variety of different research areas and applications. For instance, our analysis[12] shows that UK researchers who have cited ERSF in their publication were particularly active in Material science / physics (54%), Chemistry (46%), Methods and Instrumentation (40%) and Life sciences (39%). This suggests that not only has ESRF supported research activity across diverse disciplines (as described above), but also that there has been high research quality across disciplines too.

[10] STFC (2016) *STFC Delivery Plan 2016-2020*. Available at https://www.ukri.org/wp-content/uploads/2022/03/STFC-220316-STFCDeliveryPlan2016to20-160510-1.pdf

[11] Ibid

[12] The list of UK publications supported by ESRF does not include information on the field of study. Instead, we obtained this from LENS.org, an open-source database with patent and scholarly work records. The list of key words included in the dataset were determined based on machine learning parsing of all accessible text in the research abstract of each record. These key words were used to assign each publication into nine categories, which are shown below in Figure 5. Given the complexity of the process, we focused our analysis on the disciplines for publications in 2021. It nevertheless does give an indication of the types of research supported throughout the study period.

*Figure 5 Disciplines of research publications, 2021*




Source: ESRF monitoring data and LENS.org

Another indicator of the quality and perceived impact of a research output is whether it has been submitted for the UK Research Excellence Framework (REF). As part of the REF, a panel of expert reviewers assess submitted papers, scoring them based on their quality, impact beyond academia, and whether the overall environment has supported research. Typically, institutions will only submit papers to the REF if they believe they will score highly. It is therefore a good indication that they perceive the research to be of good quality and/or of high potential impact.

The ESRF user survey asked respondents whether they planned to submit the results from their work at the facility as part of the REF. A significant proportion, 21%, indicated that they did for the 2021 REF, while a further 13% had submitted their output as a REF case study as part of the previous REF exercise in 2014.

The vignettes below provide examples of how ESRF has enabled high-quality UK-led research with potential benefits to both industry and society.

**ESRF supporting research into the safety of lithium-ion batteries**

Lithium-ion batteries are commonly used in devices using rechargeable batteries, including mobile phones and electric vehicles. Given their wide usage in everyday life, ensuring their safety is vitally important. Research at ESRF has helped understand why batteries fail, which will help inform better safety mitigation measures.

**Background**

World-leading X-ray imaging capabilities at ESRF have enabled a collaboration between University College London, NASA, NPL, NREL and the ESRF[1], to study ways of improving the safety of lithium-ion batteries. When a battery fails, it does so rapidly, leading to its potential self-destruction.[1] Over more than five years, the team have studied many batteries, with results showing the ability to track battery damage in 2D and 3D and at high speed. At ESRF, the research team were able to test the batteries, exposing them to conditions well beyond the safe recommended operating window.[1] The objective of the research was to increase the foundational knowledge of the field, to enable the design of safety features of batteries to be evaluated and improved.[1]

**Research and scientific benefits**

There have been many fundamental insights gathered from this research. For example, the team have evaluated a solution to reduce the risk of thermal runaway, a dangerous chain reaction in lithium-ion batteries that can lead to catastrophic fires[1]. The team have also developed a greater understanding of what happens in batteries at a cell level, which is crucial to mitigating against battery failure. Moving forward the team plans to study what happens with a larger sample size of batteries, particularly looking at what changes, at a microscopic level, cause widespread battery failure.[1]

In addition, the research has produced many publications, (with the caveat that the publication reference list needs updating to reflect more accurately the number of publications to come out of this research). Additionally, the research has generated increased external collaborations for the research team and has increased their potential for funding.

**The role of ESRF**

Representatives from the research team highlighted that ESRF provides one of the brightest X-ray sources in the world. In terms of fundamental characteristics of the accelerator, they reported that "*ESRF is almost without peer in terms of the actual capability for the synchrotron radiation it generates*". It enables the research team to work faster, exercise new techniques, and conduct more experiments. The team would not have been able to carry out their research, at least not in the same way, or within the same timeframe, without the facility.

**ESRF supporting new methodological advancements for UK Catalysis Hub**

The EPSRC UK Catalysis Hub has used ESRF to pioneer new developments in imaging methodologies. Among other areas of application, the work can help the development of more effective carbon emission control in cars.

**Background**

The UK Catalysis Hub was launched using funding from EPSRC and situated at the Research Complex at Harwell. The goal for the Hub is to become a leading research centre and promoter of new breakthroughs in catalytic science.[13] The Hub's work with ESRF started from the need to access high energy X-ray beams, which ESRF was able to provide.

**The research project**

According to one of the Principal Investigators (PIs) at the UK Catalysis Hub, the research at ESRF involved analysis of material performance in operando, specifically in the area of catalyst and heterogeneous catalysts. In undertaking this analysis, members of the UK Catalysis Hub have used X-ray imaging techniques to pioneer new developments in synchrotron-based X-ray diffraction computed tomography imaging at ESRF.[14] Through ESRF usage, the Hub developed novel synchrotron-based X-ray diffraction computed tomography imaging, a major achievement in its own right.

**Potential industry usage of research**

The developments surrounding catalysts are applicable in areas related to carbon emission control, particularly within the automotive industry. As catalysts are used by car manufacturers to achieve greater efficiency in reducing harmful emissions, the work at the UK Catalysis Hub

[13] UK Catalysis Hub (2022). About Us. Available at: https://ukcatalysishub.co.uk/about-us/

[14] ESRF (2014). Illuminating the physical process of catalyst deactivation. Available at: https://www.esrf.fr/home/UsersAndScience/Publications/Highlights/highlights-2014/SOM/SOM13.html

has the potential to positively impact the automotive industry, using the fundamental research results and publications from ESRF-based work to develop improved solutions.

## 3.6 ESRF supporting UK multidisciplinary and interdisciplinary research

To explore multidisciplinary and interdisciplinary research[15] activity enabled by ESRF, we have looked at the number of publications by UK authors that have referenced ESRF, and assessed the extent to which these publications have referenced multiple disciplines or fields.[16] The evidence is clear that ESRF has regularly supported UK researchers in the development of research with either an interdisciplinary or multidisciplinary focus. Indeed, in 2021 the majority (80%) of publications had combined aspects of multiple disciplines. By way of context, research by Fire and Guestrin (2019) found that between 2010 and 2014, between c.30% and 45% of all published academic papers were multidisciplinary.[17] This suggests that ESRF has supported a higher amount of interdisciplinary research than might otherwise be expected.

On average, outputs published in 2021 by UK authors supported approximately 2.6 broad research areas. As Table 1 shows, almost half of all life sciences publications contained references to chemistry.

*Table 1 Percentage of UK-authored papers with interdisciplinary and multidisciplinary research focus, 2021*

| | Life Sciences | Medicine | Chemistry | Environmental and Earth Sciences | Material science / Physics | Methods & Instrumentation | Engineering | Cultural Heritage | Mathematics / Computer science | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Life Sciences | | 22% | 47% | 5% | 27% | 26% | 4% | 6% | 9% | 100% |
| Medicine | 65% | | 27% | 4% | 12% | 0% | 12% | 0% | 15% | 100% |
| Chemistry | 39% | 8% | | 6% | 41% | 44% | 11% | 1% | 1% | 100% |
| Environmental and Earth Sciences | 27% | 7% | 40% | | 40% | 13% | 13% | 13% | 7% | 100% |
| Material science / Physics | 19% | 3% | 35% | 6% | | 55% | 19% | 1% | 10% | 100% |
| Methods & Instrumentation | 24% | 0% | 50% | 2% | 73% | | 12% | 1% | 11% | 100% |
| Engineering | 11% | 11% | 36% | 7% | 75% | 36% | | 0% | 7% | 100% |
| Cultural Heritage | 83% | 0% | 17% | 33% | 17% | 17% | 0% | | 0% | 100% |
| Mathematics / Computer science | 39% | 22% | 6% | 6% | 50% | 50% | 11% | 0% | | 100% |

Source: ESRF monitoring data and LENS.org

The high percentage of publications that include references to multiple fields is an indicator of ESRF's success in fostering knowledge transfers among scientists with different backgrounds. It suggests that the body of scientific findings supported by access to the ESRF has relevance to a wider circle of scientists who may be working on similar problems, or to those who may use the transfer of knowledge across different domains to create new applications.

## 3.7 Ways in which ESRF has helped research

User survey respondents have helped indicate some of the specific ways that ESRF access and usage has impacted on their ability to undertake their research. As shown in Figure 6, more

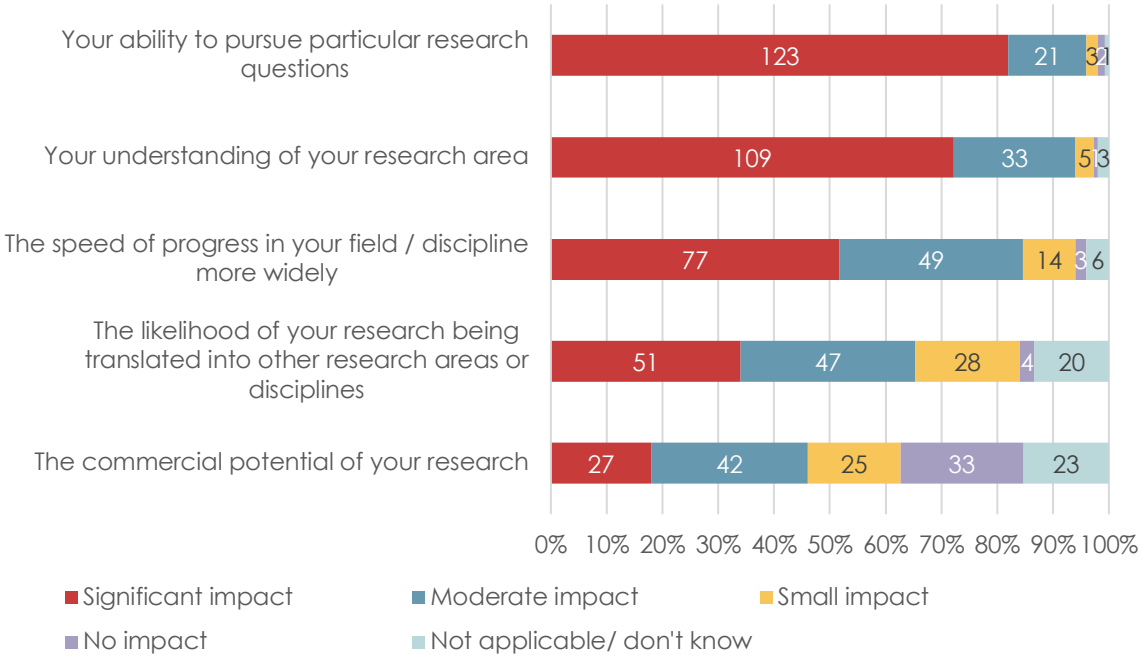
[15] Multidisciplinary research involves multiple disciplines working independently towards the same research question, but approaching it form their own discipline's perspective. On the other hand, interdisciplinary research involves two disciplines interacting and collaborating with each other to develop new theories. See https://research.ncsu.edu/rdo/the-difference-between-multidisciplinary-interdisciplinary-and-convergence-research/ for further information.

[16] We have done this by drawing on the LENS database to categorise each paper based on a list of key words describing the field of study.

[17] Fire, M. and Guestrin, C. (2019) 'Over-optimization of academic metrics: observing Goodhart's Law in action' in *GigaScience*, 8, 2019, 1-20.

than 80% of respondents stated that ESRF has had a significant impact on their ability to pursue particular research questions. Two in three also considered that ESRF had a significant impact on their understanding of their research area and had strengthened their international networks and relationships. Overall, more than 80% considered that ESRF had at least a small impact in all areas asked about, apart from the commercial potential of their research (although, even here, only 22% reported no impact at all).

*Figure 6 User survey responses to "To what extent has ESRF impacted on your own research activities?"*




Source: ESRF user survey (n=152)

Survey respondents were also asked whether their research had produced any important scientific or technological advances that would not have been possible if ESRF had not existed. Some 71% (108 of 152 respondents) indicated that they had made at least one significant scientific or technological advance directly because of ESRF. Some examples include better technical skills in relation to collecting and analysing data, published papers and reports, real time experimentation on a beamline, and real time imaging of additive manufacturing processes.

In other cases, access to ESRF has helped supplement research which has occurred at other facilities. Representatives from Diamond Light Source have spoken of how there are numerous users that draw both on it and ESRF for individual research programmes. For instance, researchers may use Diamond for more general elements of research while using the more specialised beamlines at ESRF to investigate certain elements of their work in more detail.

For others, ESRF has helped provide additional capacity (beyond the national synchrotron) when needed. Monitoring data supports this idea of ESRF supplementing research occurring elsewhere. Since 2011, UK researchers have benefited from the use of 26 different light and/or radiation facilities across the world through their collaborations with the international scientific community. Table 2 shows the top 15 most common light and radiation research facilities utilised by researchers working in collaboration with UK partners, over the past ten years.

In 2021, around two-thirds of publications cited ESRF as the only facility utilised for the purposes of their scientific research. Other than ESRF, the most cited research facilities were Diamond (16%) and PETRA III in Hamburg (7%), followed by SLS (SI) (Villigen, Switzerland) and BESSY (Germany), both at 2%.

*Table 2 Percentage of publications citing project work with other light and radiation facilities (top 15 facilities)*

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ESRF (Grenoble) Only | 67% | 64% | 59% | 62% | 63% | 65% | 65% | 69% | 64% | 67% | 66% |
| DIAMOND (Didcot) | 18% | 18% | 27% | 21% | 26% | 22% | 20% | 22% | 24% | 19% | 16% |
| PETRA III | 0% | 0% | 1% | 1% | 1% | 1% | 3% | 4% | 4% | 4% | 7% |
| SLS (PSI) (Villigen) | 4% | 5% | 4% | 4% | 4% | 4% | 2% | 2% | 3% | 4% | 2% |
| BESSY (Germany) | 2% | 0% | 2% | 2% | 2% | 2% | 1% | 1% | 2% | 1% | 2% |
| Soleil (Orsay) | 2% | 2% | 3% | 3% | 3% | 4% | 4% | 4% | 3% | 1% | 1% |
| APS (Argonne) | 2% | 1% | 1% | 2% | 1% | 1% | 1% | 1% | 2% | 1% | 1% |
| MAX-Lab (Lund) | 0.3% | 2% | 2% | 1% | 2% | 1% | 1% | 1% | 1% | | 1% |
| SRS (Daresbury) | 3% | 2% | 2% | 1% | | 1% | 1% | 0.3% | | | 0.5% |
| SSRL (Stanford) | 0.3% | 0.3% | | | 0.4% | 0.3% | 1% | | 0.4% | | 0.5% |
| SPring-8 (Nishi Harima, Japan) | 0.3% | 0.3% | 1% | 0.3% | 1% | 0.3% | 1% | | | | 0.5% |
| ALS (Berkeley) | 0.3% | | | | 0.4% | | | | 0.4% | 0.3% | 0.5% |
| NSLS (Brookhaven) | 0.3% | 1% | 0.3% | 3% | | 0% | | | 0.4% | 1% | 0.5% |
| ALBA (Barcelona) | | | | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 0.5% |

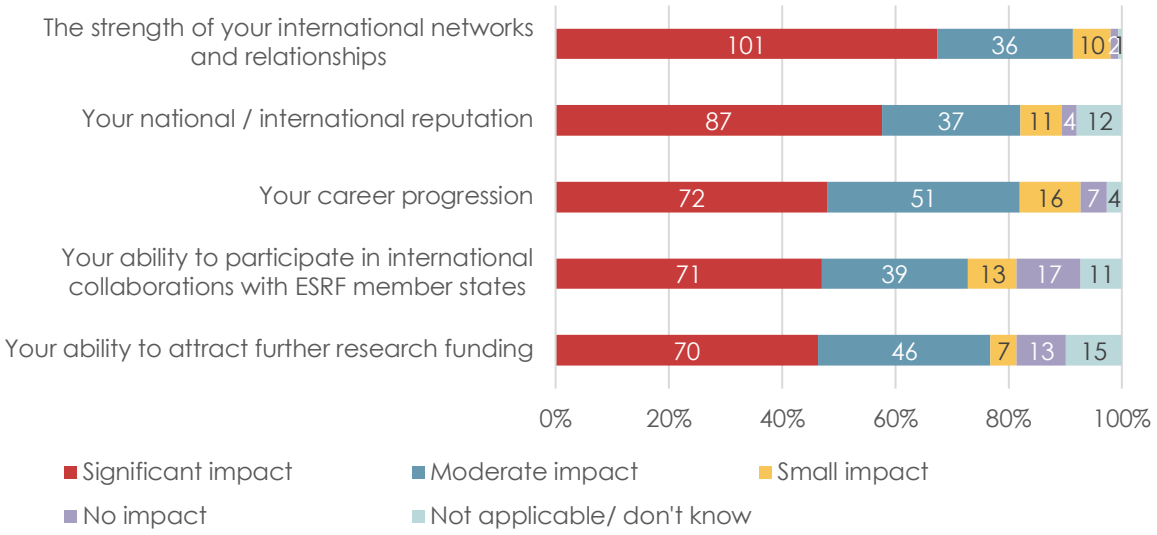
Source: ESRF monitoring data

## 3.8 Wider benefits seen to scientific community

Survey respondents also indicated that having ESRF access had benefited not only their research projects, but also wider activities that they had been involved in. It seems that ESRF access has been particularly important to researchers in network building, a point also raised by a number of interviewed stakeholders (and described in more detail in Chapter 6).

As shown in Figure 7 below, a large proportion of user survey respondents indicated that ESRF usage had strengthened their international networks and relationships – 66% said ESRF has had a significant impact in this regard, while 99% said it had had at least a small impact. Some 82% of respondents said that ESRF usage had helped improve their national or international reputation, while more than 60% of respondents to the user survey considered that ESRF has a moderate / significant impact in their ability to participate in international collaborations with ESRF member states.

*Figure 7 User survey responses to "To what extent has ESRF impacted on your own research activities?"*




Source: ESRF user survey (n=152)

# 4 Skills impacts amongst users

The UK's involvement in ESRF has helped improve both UK researchers' own skills as well as wider scientific skills across the UK user community. This section explores both of these areas of benefit.

## 4.1 Summary

- Access to ESRF has played a very important role in developing the wider skills and capabilities of UK-based researchers, particularly in terms of their ability to undertake research at this and similar facilities in future. Stakeholders have consistently spoken of the quality of staff at ESRF to help guide them on how to best use different instruments
- ESRF has been particularly important in training early career researchers, with UK researchers also having benefitted from PhD programmes there
- A number of UK school-aged students have also benefited from the successful and well-regarded XMaS Scientist Experience scheme which has helped encourage young females to pursue science-based careers.

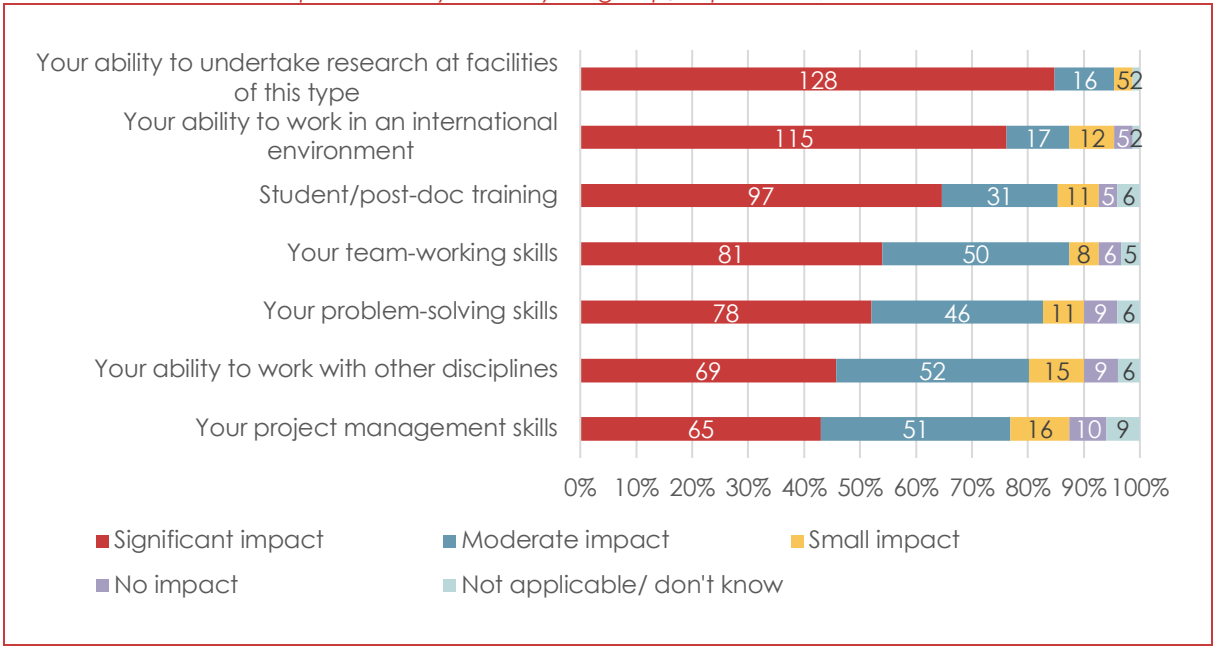
## 4.2 Improving user skills

In the previous section, we outlined the role that ESRF access has played in helping to improve users' knowledge of their subject area, leading in some cases to important scientific breakthroughs. Through interviews and surveys, many users have also spoken of how usage of ESRF has improved the broader scientific and research skills of users and their research teams.

As Figure 8 shows, almost 90% of respondents to our user survey stated that their involvement with ESRF had at least a small positive impact on them in all of the listed skills and capabilities, as well as on their group or department. In particular, 80% reported a significant impact on their ability to undertake research at similar facilities. Interview evidence has helped reveal more on how ESRF access has specifically helped improve skills and capabilities here. Several consultees have spoken of the quality of the staff at ESRF, who have helped guide researchers on how to use the different instruments most effectively and efficiently. Indeed, one consultee said that such was the level of quality of interaction with ESRF staff, that they co-authored articles with them. Another consultee, a palaeontologist, spoke of how use of ESRF had deepened their understanding of synchrotrons and how they could benefit their research going forward, where they had previously relied on a local MRI scanner.

As shown, 70% of survey respondents also highlighted how working at ESRF had improved their ability to work in an international environment. There was a strong consensus amongst interviewees that one of ESRF's strengths was being a cross-disciplinary international facility. It provided an opportunity to work, and indeed have informal conversations with, researchers that they otherwise would not have access to. Consultees said that the setting offered by ESRF was especially beneficial to early career researchers in this regard.

*Figure 8 Survey responses to "To what extent has your involvement with ESRF had a positive impact on the skills and capabilities of you and your group/department, in terms of:"*




Source: ESRF survey data

## 4.3 Effects on early career researchers

Consultees were clear that ESRF played a particularly important role in the skills development of early career researchers[18]. Several user survey respondents spoke of how ESRF access had been critical in enabling them to complete their PhDs. Interviewed and surveyed senior researchers and principal investigators also emphasised the centrality of ESRF in training PhD students and post-doctoral researchers. They spoke of it introducing them to using very complicated research apparatus, as well as wider aspects needed to successfully run experiments, such as computer control, autonomation, instrumentation, programming, and health and safety. It is particularly helpful for these individuals to 'learn by doing' rather than being simply taught these elements in a more theoretical manner. One senior researcher spoke of how, whenever they visited ESRF, they would have a team of 2-3 early career researchers with them. From this we can also infer that many early careers researchers are likely to visit ESRF and in turn benefit from the skills development opportunities it provides.

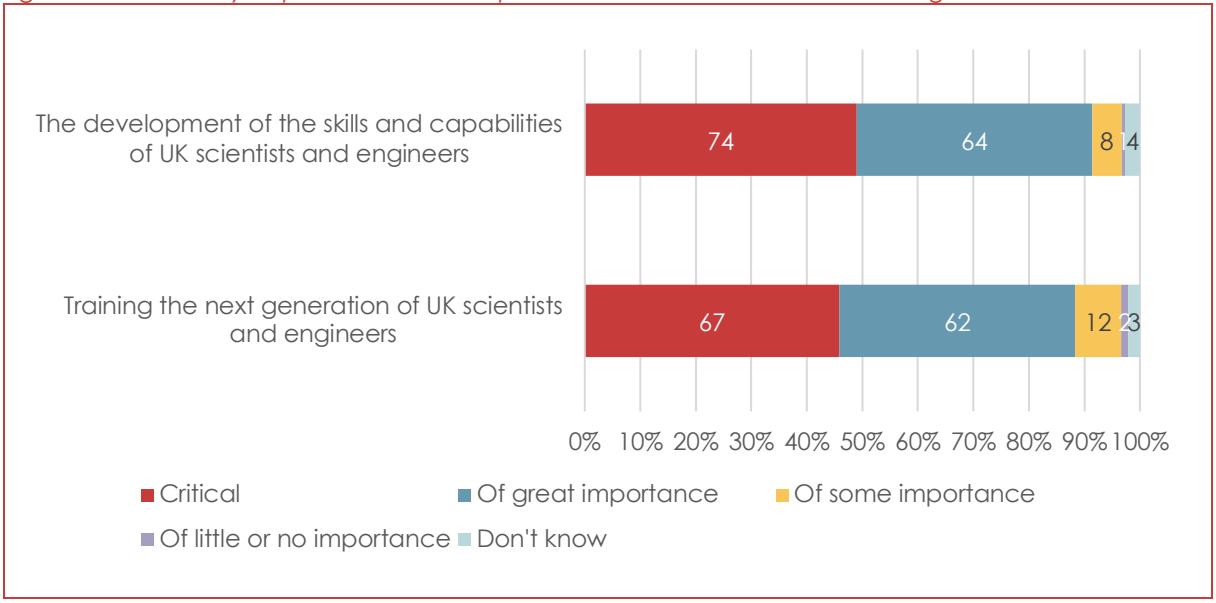
Aside from informal training provided by researchers themselves, ESRF has also led the InnovaXN programme, which provides an opportunity for 40 industrial companies to work with 40 PhD students on synchrotron X-rays and neutrons.[19] Programme monitoring data shows that the programme has so far supported eight students from the UK.

Interviewee sentiments on early career benefits chime with findings from the user survey. As shown in Figure 9 below, over 90% of respondents believe that ESRF has either been 'critical' or of 'great importance' in both developing the skills and capabilities of current UK scientists and engineers, and in training the next generation.

[18] There is no common definition of an early career researcher but is traditionally considered to be someone who is commonly within eight years of their PhD award. Some also view PhD candidates as also falling within this category.

[19] https://www.innovaxn.eu/programme-partners/

*Figure 9 User survey responses to "How important has ESRF been to the following?"*




Source: ESRF survey data (n=151)

## 4.4 The role of outreach programmes in improving skills

ESRF is involved in outreach programmes which have helped to improve the science skills and capabilities of groups that are outside the facility's core user base. Every year it runs an International Summer Student Programme on X-ray and neutron science in collaboration with the Institut Laue-Langevin (ILL). A four-week programme, it embeds undergraduates in a research group at ESRF and provides them with introductory lectures on the principles of neutrons and X-rays, as well as the opportunity to work on specific scientific projects tutored by ESRF scientists.[20] The programme is only open to undergraduate students from a Member Country, meaning that UK students are amongst those able to benefit from it.

Several consultees, both stakeholders and users, have also commented on the quality of outreach work that ESRF has undertaken with school aged students. They especially highlighted the work of the XMaS Scientist Experience scheme (see box below), which XMaS, the UK Materials Science Facility at ESRF, has run since 2012. The scheme is a national competition for Year 12 physics students, offering them a chance to win a fully funded four-day trip to ESRF with the aim of encouraging school-aged females to pursue a career in science. XMaS representatives have spoken of the scheme's success, with it receiving good social and local media coverage, and being well received by ESRF staff too. XMaS felt that the programme had been so successful that they are now looking to expand the programme.

**The XMaS Scientist Experience Scheme**

**Background**

Since 2015, the XMaS national research facility staff have successfully developed an outreach programme aimed at tackling gender bias in Physics. They run an annual national competition, resulting in a group (typically numbering sixteen) of 16-18 year old female students taking a trip to visit the European Photon and Neutron campus in Grenoble, and touring both the ESRF and

[20] https://www.esrf.fr/home/education/summer-student-programme.html (accessed 3 November 2022)

the XMaS beamline. Participants conduct mini research projects, give a presentation, tour the campus, and meet female scientists working at the facility.

**Impacts seen**

According to programme representatives, the main benefit for the participants is being surrounded by other like-minded science enthusiasts, helping to build up confidence in their own aspirations. The initiative also gives the students a positive image of a career in science, giving them something to aim for. The students create a WhatsApp group where they chat to each other, and stay connected even after the event.

According to the programme staff, as a result of the trip, the students' perceptions and stereotypes of people working in STEM careers is challenged. They see, often for the first time, the collaborative nature of working in the sciences first hand, in contrast to the perception that many hold of life as a scientist being an isolating experience. The opportunity also provides an inspirational setting to see science 'beyond the classroom', but with direct relevance to the school curriculum on the one hand and research in the 'real world' on the other.

Additionally, the students see how ESRF provides a space for international collaboration, co-working and interdisciplinarity, which the XMaS team is keen to showcase to young female students contemplating a career in science.

## 4.5 Improved skills and capabilities amongst the wider community

Stakeholders and users alike have also commented on how UK access to ESRF has contributed to an improvement to the wider user skills base outside that of research groups using the facility. As shown in Table 3 below, 51% of user survey respondents highlighted the critical importance of ESRF as a vehicle to advance knowledge amongst the UK scientific community. Overall, 99% acknowledged at least some importance of the facility in this regard.

*Table 3 User survey responses to "How important has ESRF been to advancing knowledge amongst the UK scientific community"*

| | Number | Percentage |
|---|---|---|
| Of little or no importance | 1 | 1% |
| Of some importance | 11 | 7% |
| Of great importance | 59 | 39% |
| Critical | 77 | 51% |
| Don't know | 3 | 2% |
| Total | 151 | 100% |

Source: ESRF survey data

# 5 Tackling wider UK policy & strategic objectives

Although not originally anticipated as a central impact pathway during the scoping phase, as the study has progressed, it has become clear that ESRF has played, and will continue to play an important role in meeting the strategic goals of STFC (particularly around the development of world-class multidisciplinary facilities in Diamond, and in fostering collaboration opportunities for the UK), as well as other much broader government policies.

## 5.1 Summary

- The UK's involvement in ESRF has led to spillover benefits to Diamond and other UK research facilities, most notably by providing experience, technologies, and best practices that can inform the development of other UK research infrastructures such as Diamond II, as well as training staff that later have gone on to work at national facilities
- ESRF has also played a role in helping STFC meet its strategic goals to strengthen the UK's research and innovation community, particularly in relation to early career researchers and access to international networks and opportunities
- The UK's interactions with ESRF have also helped contribute towards some long-standing wider government policy priorities including:
  - Producing the technologies that will help decarbonise the economy
  - Supporting businesses based outside the south-east, helping with levelling up
  - Supporting SME growth, by providing them with contract opportunities to supply the facility
  - Helping fulfil UK aims to become a science superpower by 2030
  - Improving healthcare

## 5.2 ESRF's contribution to the development of world-class multidisciplinary facilities

As noted in their 2022-2025 Strategic Delivery Plan, one of STFC's strategic objectives is "*developing and deploying world-class national multidisciplinary facilities, leading the UK's participation in international infrastructures.*"[21] Continued UK access to ESRF remains part of the strategy for meeting this goal, but so does continued support for Diamond Light Source which STFC sees as a vital part of its portfolio.[22]

While Diamond provides a different and complementary offer to ESRF, focused on higher throughput and soft X-ray techniques, knowledge exchange between ESRF and Diamond has led to improved functioning and capabilities for Diamond. This includes:

- **Better informed plans for the Diamond upgrade**: Representatives from Diamond spoke of how planning for the Diamond upgrade, commonly referred to as Diamond II, has drawn heavily on experiences seen at ESRF. They noted that ESRF had been the first facility to undergo a major upgrade while still operational, and as such there was a considerable amount of learning and best practice to be gained which could be applied to Diamond. The level of engagement between the two facilities will also ensure that Diamond II provides next generation capabilities which supplement and complement the ESRF offer rather than duplicating it. This will in turn help UK researchers have access to the widest range of synchrotron facilities and functions possible between the two sites.

[21] Science & Technology Facilities Council (STFC) and UK Research and Innovation (UKRI) (2022) *Delivery Plan*, p.7. Available at https://www.ukri.org/wp-content/uploads/2022/09/STFC-010922StrategicDeliveryPlan2022.pdf (accessed 8 November 2022)

[22] Ibid. p.14

- **Providing Diamond with a pool of talented staff**: Consultee feedback was that a large number of Diamond's scientists have previously trained at ESRF. They highlighted that the facility has provided a stream of good scientists which in turn, has allowed Diamond to run more effectively and efficiently than it might have done otherwise.
- **Sharing of knowledge, ideas and technology**: Diamond has seen ESRF as a technological collaborator, drawing on its insights and expertise to help deliver improved technologies and solutions at Diamond itself. Diamond and ESRF are also members of the League of European Accelerator-based Photon Sources (LEAPS), a collaboration of 19 light source facilities across Europe which produces road maps for the development of next generation light sources and instrument technologies, and makes the case for their funding.[23] Diamond and ESRF scientists also worked with each other on the development of the cryo-electron microscope at ESRF. Furthermore, as part of its upgrade, Diamond plans to build on some of the technological development incorporated into the ESRF upgrade, especially with regards to software design, optics design, and the use of robotics in the running and management of experiments. The proposed storage ring for the Diamond upgrade is also being modelled on the one that ESRF developed for its own upgrade to EBS. A number of UK suppliers have also been involved in the design and supply of magnets for ESRF's upgrade, which should form a good basis for the future Diamond upgrade too.

Stakeholders also spoke of there being some potential spillover benefits from ESRF to UK facilities other than Diamond. Largely, this focused on other facilities gaining from the training of staff at ESRF, as well as ESRF providing some complementary measurements for UK-based research.

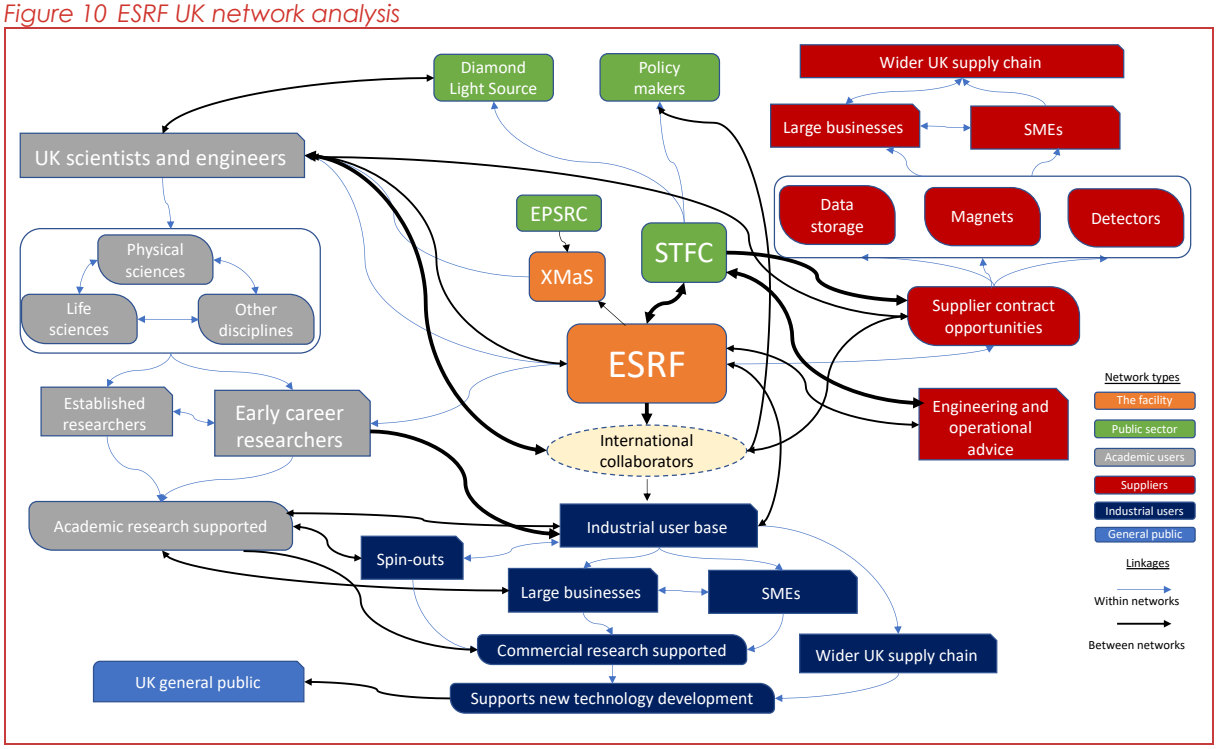
## 5.3 ESRF's contribution to building stronger research and innovation partnerships

STFC's 2022 Delivery Plan also states ambitions for creating *"The conditions for an outstanding research and innovation system."* This includes creating thriving ecosystems, better connected industry and academia, and creating better links between research and the general public.[24] ESRF has played an important role in this, helping create a more joined up scientific community within the UK, as well as enhancing connections internationally. Figure 10 provides a network analysis for ESRF, summarising the different UK networks that have benefited either directly or indirectly from ESRF access, as well as the links that have formed between different network communities

[23] LEAPS (2017) *Light Sources for Europe: Strengthening Europe's leading role in science and innovation*, p. 2. Available at https://leaps.clients.naamstrom.com/wp-content/uploads/2019/11/LEAPS-Brochure.pdf (accessed 23 August 2022)

[24] Science & Technology Facilities Council (STFC) and UK Research and Innovation (UKRI) (2022) *Delivery Plan*, p.7. Available at https://www.ukri.org/wp-content/uploads/2022/09/STFC-010922StrategicDeliveryPlan2022.pdf (accessed 8 November 2022)

*Figure 10 ESRF UK network analysis*




Source: Technopolis. Note that thicker arrows denote more important and stronger links

There are a number of mechanisms that are central to this community existing in the way that it does:

- **Centrality of STFC**: STFC has a number of links to ESRF which creates knock-on benefits for others, both in the public sector and in other networks. As a strategic partner of ESRF, STFC has been able to share knowledge and ideas with researchers and management staff at ESRF which can inform wider strategies, including how to improve Diamond Light Source. STFC has also created links for the suppliers' network. Not only is STFC an important supplier of ESRF in its own right (including engineering and operational advice, and provision of specialised software), it is also a conduit and facilitator for bidding opportunities for UK suppliers.
- **The interaction of UK scientists and engineers across multiple networks**: ESRF has played a pivotal role in supporting the development of knowledge, skills, and capabilities of UK scientists and engineers in fundamental science. Fundamental research provides the building blocks for a variety of different applications, meaning that multiple networks have sought to draw on their ESRF-developed expertise. UK scientists and engineers have contributed to outputs for the academic community, but have worked closely with ESRF suppliers and industrial users, with both groups having valued access to improved fundamental knowledge.
- **The role of early career researchers**: as noted in previous sections, early career researchers have been amongst the groups that have benefited the most from having access to ESRF. They have had a chance to contribute to high profile research projects by working at ESRF, and have also had an opportunity to learn new scientific and work skills. Much of this knowledge and these skills are relevant to industry, meaning that industry is often keen to take on those that have trained at ESRF.
- **The importance of international collaborators**: arguably one of the most important players in this research community are international collaborators, be they international researchers, or science policy makers in other countries. From a research perspective, ESRF

has been an important conduit in ensuring the UK has access to international collaborators, which has helped shape the outputs generated across all the other UK-based networks.

- **Development of societally relevant research:** ESRF has enabled both academia and industry to undertake research on themes that are societally relevant, addressing everyday issues such as healthcare, transportation, and cultural heritage. To that end, the UK's involvement in ESRF is contributing to tackling societal concerns that the UK general public faces.

## 5.4 Meeting government policy priorities

The UK's involvement in ESRF has also helped the country deal with a number of government policy priorities:

- **Decarbonising the economy:** the Government has a long-standing commitment to reach net zero carbon emissions by 2050. As part of this, the 2021 *Net Zero Strategy* emphasises the need to support innovation and R&D activity, including early stage research that can provide the technologies, processes and services needed to decarbonise the UK economy.[25] ESRF has supported a number of UK research projects that are relevant to this strategy. These include research centred on improving the performance of lithium-ion batteries, and the development of new hydrogen fuel cells. Such research projects are in line with the types of activity advocated in the *Net Zero Strategy*. Some interviewed stakeholders have also spoken of the benefits of ESRF being a geographically proximate facility, which reduces the need for long distance travel to use other synchrotrons in the United States, for example.
- **Levelling up:** the 2022 *Levelling Up Strategy* focuses on creating and spreading economic opportunities across all parts of the UK – in recent times economic growth and high productivity has tended to be over-concentrated in specific areas, particularly the South East of England.[26] Interviewed stakeholders have commented on how organisations across the country have won contracts to supply ESRF. As noted previously in Table 5, Wirral-based AMF Precision Engineering has secured an especially large amount of ESRF contracts, showing that the facility has created economic opportunities outside traditional innovation clusters around Harwell.
- **Supporting SMEs**: the 2021 *Plan for Growth*[27] stresses the Government's plan to support the development of, and opportunities for, SMEs. Discussions with stakeholders and an examination of ESRF monitoring data has shown that many ESRF contracts have been awarded to UK SMEs, thereby helping address this policy priority.
- **Becoming a science superpower**: In March 2021, the Government set an ambition to be recognised as a Science and Technology Superpower by 2030, "remaining at least third in the world in relevant performance measures for scientific research and innovation, and having established a leading edge in critical areas."[28] Stakeholders inside government have spoken of how they view ESRF as being a valuable asset to UK science, providing the means to produce some of the high quality and high impact research that will help the UK achieve this science superpower goal.
- **Improving healthcare**: UK researchers have worked on projects which have used ESRF to help study different diseases, with the work in turn expected to inform improved treatments.

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[25] HM Government (2021) *Net Zero Strategy: Build Back Greener*

[26] HM Government (2022) *Levelling Up the United Kingdom: White Paper*

[27] https://www.gov.uk/government/publications/build-back-better-our-plan-for-growth

[28] HM Government (2021) *Global Britain in a competitive age: The Integrated Review of Security, Defence, Development and Foreign Policy*, p. 7

Most notably, UK researchers have led the Human Organ Atlas research project (as outlined below), which has used ESRF to examine the ways that COVID-19 altered lung vessels. Project researchers also expect that ESRF usage will enable them to study treatments for Alzheimer's, while other researchers spoke of how their research at the facility could help diagnose osteoporosis and glaucoma at earlier stages than currently possible.

**ESRF and the Human Organ Atlas**

**Background**

The Human Organ Atlas is a University College London led research project which has developed a new methodology, Hierarchical Phase-Contrast Tomography (HiP-CT), to improve the understanding of the human anatomy. It is looking to produce high quality, 3D images of the human body, considering parts of the body from everywhere between the micron level to the whole intact organ level. The study has its roots in a technique developed by the ESRF beamline scientist, Paul Tafforeau, to produce high resolution images of biological specimens. A research team, led by University College London, looked to take this approach and apply it to the human lung, specifically to study the effects of COVID-19 on the organ. The research has been a high-profile project, attracting international attention both inside and outside academia.

**Impacts seen on healthcare**

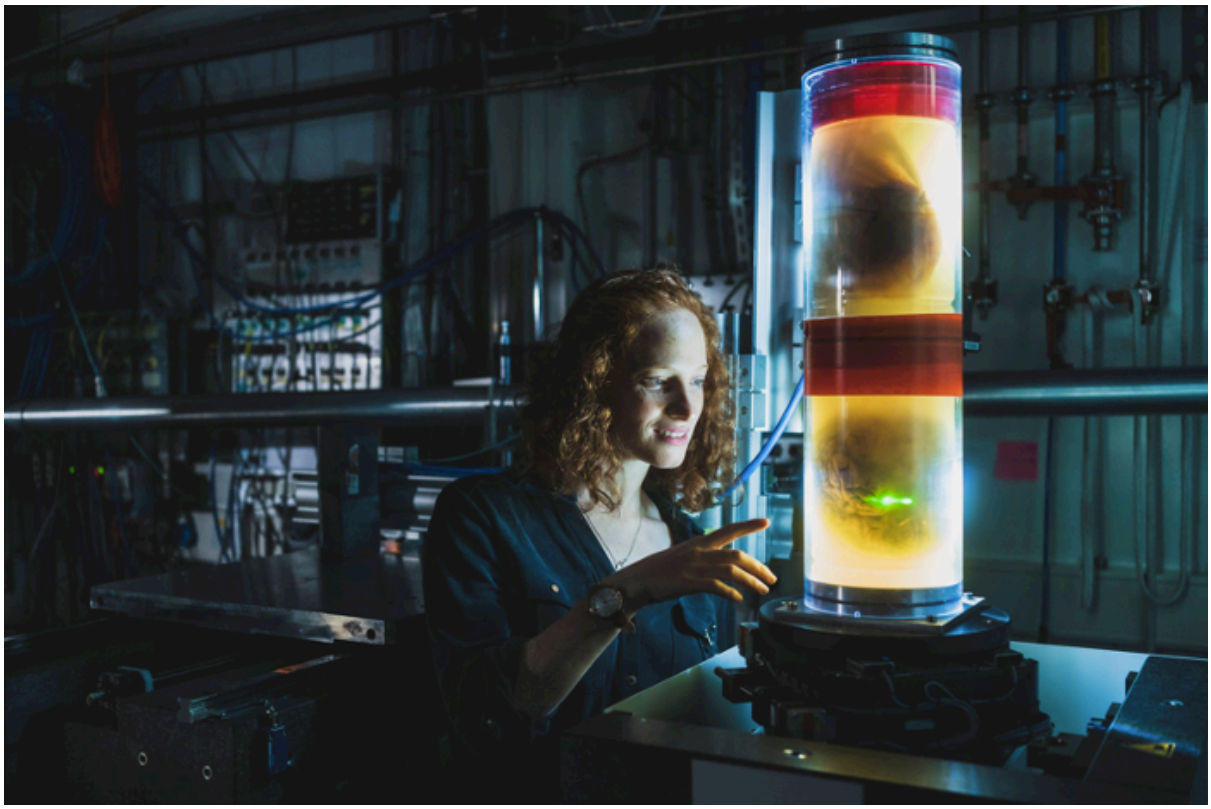
Arguably some of the research project's most notable impacts have been in terms of advancing healthcare treatments. The work helped improve the understanding of how COVID-19 infection damages lungs, and also provided evidence on how COVID-19 leads to muscle disease in the heart. Consultees also spoke of how they expect the HiP-CT methodology developed through work at ESRF to help improve the understanding of Alzheimer's Disease (by being able to quantify changes in white and grey matter in the brain, and the presence of amyloid plaques), and of cancers.

Consultees also believed that there is a potential for spillover benefits to the healthcare system. There is hope that the methods used in HiP-CT could help inform the interpretation of MRI scans, and enable better 3D imaging of biopsy samples for instance. While there was an acknowledgment that very few places could provide the quality of equipment that ESRF does, there was a belief that a version of HiP-CT could potentially be used in national centres which had facilities similar to that of a synchrotron.

**The importance of the facility**

ESRF's upgrade to EBS means it now has the low-emittance, high-energy light source to penetrate an entire large human organ such as the heart. Research group representatives were clear that some of their imaging would only have been possible through ESRF given the upgrade to EBS.

Consultees also spoke of the added value that ESRF provided in terms of the quality of its staff, and the quality of sample treatment facilities available too. By working with staff at ESRF, the research team have developed knowledge of how to pre-treat organs before experiments, something which they believe can help inform all future ex situ soft tissue radiography going forward.



All credits for this photo are ESRF/Stef Candé, with use restricted to ESRF or ESRF-Related communications, to all communication on this project in which the ESRF is involved and mentioned

# 6 UK's international standing

Drawing on the evidence gathered, it is clear that the UK's involvement in ESRF has helped contribute to the UK's international standing within the science community in particular. As outlined below, the UK's involvement has helped not only enhance the UK's reputation amongst peers, but also provided opportunities for international collaboration that would otherwise have been difficult to achieve.

## 6.1 Summary

- Access to ESRF has given the UK greater resilience and security in accessing leading scientific research facilities, and access to the broad suite of capabilities existing across multiple synchrotrons
- There are soft power gains for the UK too, with its involvement in ESRF ensuring it maintains influence in international science decision making
- Involvement in ESRF has also created international collaboration opportunities. Indeed, levels of international collaboration amongst UK researchers have increased over time
- Membership of ESRF has also enhanced the UK's reputation as a centre of scientific research. ESRF has an excellent worldwide reputation and by being able to associate itself with it, the UK's own reputation improves

## 6.2 Ability to lead internationally important research

ESRF is one of the world's leading synchrotron facilities, offering a light that is much brighter than in other facilities. Diamond – the UK-based light source – is a lower energy machine than ESRF (3GeV compared to ESRF's 6GeV), but it can accommodate a larger volume of UK researchers than ESRF. Interviewed stakeholders have therefore been clear that the UK has been able to stay at the forefront of international science because it has been able to use both Diamond and ESRF in tandem – the same opportunities would not have been possible had the UK only had access to one facility. ESRF alongside Diamond has given UK researchers access to the full set of synchrotron capabilities: a higher capability facility through ESRF, and a higher capacity facility in Diamond which is better tailored to UK needs. Indeed, multiple interviewees have spoken of significant papers having been published which have used both ESRF and Diamond (see also Table 2 above). Even prior to ESRF's upgrade, STFC's 2016-2020 Delivery Plan highlighted the need to maintain access to both Diamond and ESRF, while separately noting that the UK's "access to powerful and unique multidisciplinary facilities [like ESRF] …will complement…Diamond."[29]

Stakeholders have also spoken of how having access to both ESRF and Diamond offers greater resilience to UK researchers. For instance, during the upcoming upgrade to Diamond, UK researchers will still have access to beamline time at ESRF, ensuring there is less interruption to research activity and in turn helping the UK remain competitive with other countries in its research. The reverse was true during the ESRF shutdown. Even once the upgrade of Diamond is complete, stakeholders have been clear that the ESRF will still have an important role to play in UK-led science. Diamond II will have a much broader remit than ESRF and therefore will not have some of the specialised facilities that ESRF does. Therefore, UK researchers will still need access to the opportunities that both facilities provide together.

Another stakeholder also spoke of the role that ESRF plays in helping showcase the UK's abilities at leading and managing international science projects effectively and efficiently. By sitting

[29] STFC (2016) *STFC Delivery Plan 2016-2020*. Available at https://www.ukri.org/wp-content/uploads/2022/03/STFC-220316-STFCDeliveryPlan2016to20-160510-1.pdf

on the ESRF Council, STFC is able to showcase its best practice in research management and governance (e.g. the plans it has in place to become net zero by 2040).[30]

## 6.3 Maintaining the UK's influence in international science

Some stakeholders suggested that the UK's exit from the European Union had made it much more difficult for the UK to engage with and shape science programmes that receive European Commission funding. With the UK no longer financially contributing to such programmes, there is a risk of the UK losing influence as a result. However, the UK's involvement in ESRF helps mitigate against this risk. By financially contributing to the facility, the UK remains party to some discussions around the future of European science and is able to influence these too. Some stakeholders have spoken of how the UK's financial involvement in the facility helps the UK come across as being more internationally open, and more connected to the European context. This is especially helpful as the UK tries to secure associate status with Horizon Europe.

## 6.4 Creation of international collaboration opportunities

Interviewed stakeholders have commented on how the ability of UK researchers to work at ESRF has helped create international collaboration opportunities. As an internationally used facility, ESRF brings researchers from across the world into a single space. This has led to an international cross-fertilisation of knowledge, contacts and ideas which the UK has benefited from. Indeed, some interviewees have argued that part of the reason that ESRF has produced such leading-edge science is because of its international focus.

User survey respondents also overwhelmingly highlighted that the international dimension of ESRF was one of the most notable positives to come from the facility. They spoke about how access to ESRF has helped develop and maintain relationships with international collaborators and research groups across Europe, not only in preparing and undertaking set research projects, but also through sharing space and facilities with others at the site itself. Some respondents spoke in particular about the importance of building such international networks for early career researchers, including the increased visibility that being part of ESRF gives them in European research groups.

A study of academic papers published by UK researchers that have used ESRF confirms the fact that the facility has helped foster a number of important international collaboration opportunities. Examining all 203 papers with a UK author who cited ESRF in their publication in 2021, we see that the majority (92%) included at least one international partner. On average, UK researchers have worked with approximately three international collaborators on each paper based on ESRF research, with roughly a fifth of UK publications reporting four or more authors from foreign countries. In 2021, UK researchers were most likely to collaborate with authors in ESRF (49%) and in Germany (32%). Outside of Europe, the most common co-author countries were the US (23%), South Africa (7%), and Canada (7%).

As Table 4 below shows, over time UK researchers have become more likely to engage with international researchers. The share of publications involving no international partners has decreased substantially between 2011 to 2021 (25% to 8%). It seems that collaborations have particularly increased with ESRF itself (a 17-percentage point increase over the same period), and Germany (a 15-percentage point increase).

*Table 4 Percentage of publications co-authored with UK researchers (top 15 author countries)*

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|---|---|---|

[30] See https://www.ukri.org/news/green-transformation-for-uk-science-estate/

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ESRF staff (France) | 31% | 29% | 34% | 36% | 38% | 38% | 38% | 34% | 40% | 45% | 49% |
| Germany | 16% | 14% | 18% | 25% | 21% | 23% | 22% | 25% | 23% | 28% | 32% |
| France (not ESRF) | 22% | 18% | 22% | 26% | 18% | 28% | 24% | 24% | 25% | 25% | 29% |
| USA | 16% | 10% | 15% | 18% | 12% | 17% | 17% | 14% | 19% | 18% | 23% |
| Italy | 7% | 9% | 7% | 6% | 6% | 10% | 8% | 8% | 6% | 9% | 10% |
| Switzerland | 5% | 6% | 5% | 6% | 7% | 6% | 5% | 7% | 7% | 9% | 10% |
| **UK only** | **25%** | **27%** | **25%** | **24%** | **22%** | **16%** | **15%** | **13%** | **13%** | **12%** | **8%** |
| Sweden | 3% | 4% | 6% | 4% | 5% | 6% | 5% | 7% | 8% | 10% | 7% |
| South Africa | 1% | 1% | 1% | 1% | 1% | 2% | 1% | 2% | 3% | 2% | 7% |
| Canada | 2% | 2% | 3% | 6% | 1% | 3% | 2% | 3% | 5% | 1% | 7% |
| Australia | 3% | 5% | 2% | 3% | 4% | 2% | 4% | 2% | 3% | 3% | 6% |
| Netherlands | 3% | 5% | 7% | 7% | 5% | 6% | 5% | 5% | 5% | 5% | 6% |
| China | 2% | 2% | 2% | 3% | 3% | 3% | 4% | 6% | 6% | 6% | 5% |
| Japan | 3% | 4% | 1% | 6% | 4% | 4% | 4% | 5% | 4% | 4% | 5% |
| Austria | 2% | 1% | 3% | 3% | 1% | 3% | 2% | 2% | 2% | 3% | 4% |

Source: ESRF monitoring data

## 6.5 Improving perceptions of the UK as a centre of scientific research

Several respondents to the ESRF user survey have commented on the reputational benefits that the UK gains by being able to associate itself with a world-leading facility like ESRF. Common perceptions of ESRF are of it being a dynamic facility which brings together world-leading scientists from a variety of different disciplines. There was some concern amongst not only users, but also from interviewed stakeholders, that the UK would suffer some reputational damage were it ever to withdraw from ESRF. It would be seen as isolating itself from the wider international community, and would in turn, make the UK less attractive for leading researchers from around the world.

There was recognition also that the UK benefits from knowledge and personnel flows from ESRF (as described earlier, the movement of ESRF scientists to the UK greatly aided the development of Diamond). The UK's international reputation is therefore likely to have improved because it has scientists that have been trained in a world-renowned institution.

# 7 Benefits to the UK in supplying ESRF

A number of UK companies have benefited from securing large-scale contracts to supply ESRF with goods and services. This chapter sets out the types of UK organisation that have supplied ESRF, and the contributions that these opportunities have made to the UK economy.

## 7.1 Summary

- The UK has sold a range of different goods and services to ESRF over the last ten years, from magnets used on the beamlines themselves, to software and control systems, and instruments
- ESRF has had a diverse range of UK suppliers, encompassing the public sector, engineering and manufacturing firms, and software firms
- Between 2015 and 2021(the period for which data are available), UK suppliers to ESRF have won contracts worth nearly €16 million. The UK's rate of industrial return averaged out at 0.7 over this period
- The ESRF contracts have also been important in helping UK firms develop the skills and market visibility needed to secure contracts outside ESRF. This expertise will also enable UK firms to supply Diamond II in the future.

## 7.2 Nature of goods and services provided to ESRF

Because the UK makes financial contributions to the facility, ESRF itself tries to ensure that the UK has fair access to contract opportunities. As a result, the UK has provided a range of different goods and services to ESRF over the study period, spanning from magnets used on the beamlines themselves, to software and control systems, and instruments. According to interviewed stakeholders, the UK has been particularly prominent in the provision of technical skills to ESRF and won a particularly large number of contracts associated with the ESRF upgrade to the EBS.

ESRF monitoring data shows that between 2015 and 2021, 20 organisations have accounted for approximately 75% of ESRF's total spend on UK suppliers. Tesla Engineering, suppliers of magnets to the facility, accounted for approximately half the total value of contracts to UK suppliers (their experience is explored further later in this section). AMF Precision Engineering (also profiled later in this section) accounted for the next largest share at 6.7%. Beyond this, as shown in Table 5, ESRF has had a diverse range of UK suppliers encompassing the public sector, engineering and manufacturing firms, and software firms.

*Table 5 Top 20 UK suppliers (by contract value) to ESRF, 2015-2021*

| Rank | Supplier | Description | Total € | % of total spend on top 20 UK suppliers | Cumulative% |
|---|---|---|---|---|---|
| 1 | Tesla Engineering Ltd | Magnet Engineering | 7,951,979 | 50.6% | 50.6% |
| 2 | AMF Precision Engineering Ltd | Precision engineering | 1,059,244 | 6.7% | 57.3% |
| 3 | IOP Institute of Physics Publishing | Academic publishing | 379,757 | 2.4% | 59.7% |
| 4 | Instrument Design Technology Ltd | Scientific equipment | 344,170 | 2.2% | 61.9% |
| 5 | STFC | Public sector | 343,110 | 2.2% | 64.1% |
| 6 | VACGEN Ltd | Vacuum manufacturing | 250,121 | 1.6% | 65.7% |

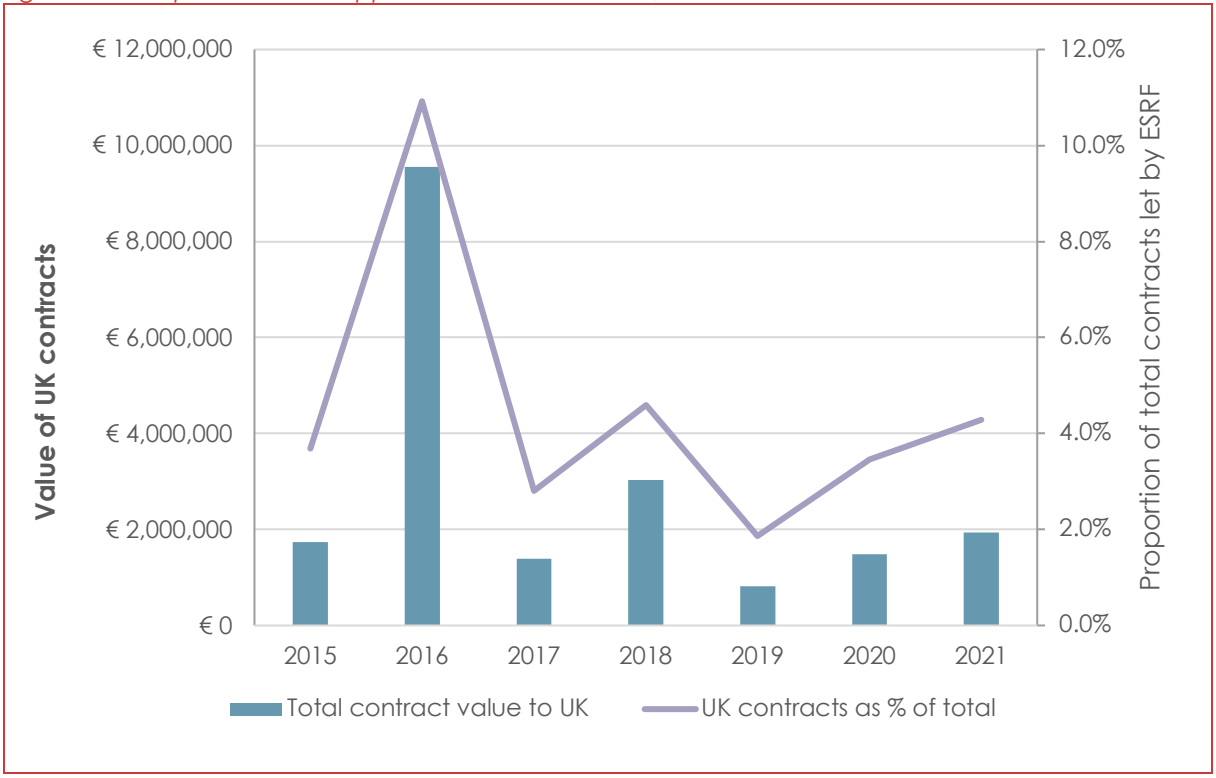
| Rank | Supplier | Description | Total € | % of total spend on top 20 UK suppliers | Cumulative% |
|---|---|---|---|---|---|
| 7 | Kurt J Lesker | Vacuum products | 218,789 | 1.4% | 67.1% |
| 8 | Oxford Instruments Nanoscience | Research instrument design and manufacture | 216,955 | 1.4% | 68.5% |
| 9 | Oxford Cryosystems | Laboratory equipment supplier | 154,744 | 1.0% | 69.5% |
| 10 | UHV Design Ltd | Machining manufacturer | 136,438 | 0.9% | 70.3% |
| 11 | Inca Geometric | Machining and assembling | 135,516 | 0.9% | 71.2% |
| 12 | RaySpec Ltd | X-ray detector manufacturers | 135,240 | 0.9% | 72.1% |
| 13 | Clearvision CM | Software company | 127,616 | 0.8% | 72.9% |
| 14 | Ngoar UK Limited | Software company | 118,246 | 0.8% | 73.6% |
| 15 | Photonic Science | Scientific imaging systems manufacturers | 75,497 | 0.5% | 74.1% |
| 16 | Edmund Optics | Optics and imaging manufacturers | 74,858 | 0.5% | 74.6% |
| 17 | UK Atomic Energy Authority | Public sector | 67,990 | 0.4% | 75.0% |
| 18 | UKRI | Public sector | 67,771 | 0.4% | 75.4% |
| 19 | April Six Proof Ltd | Public relations | 64,945 | 0.4% | 75.9% |
| 20 | Zone Plates Ltd | Optical elements fabrication | 63,593 | 0.4% | 76.3% |
|  | Total |  | 11,986,578 | 76.3% |  |

Source: ESRF monitoring data (as supplied to the study team)

## 7.3 Commercial and economic effects of supplier activity

As shown in Figure 11 below, between 2015 and 2021, UK suppliers to ESRF have won contracts worth nearly €16 million, equating to 6% of all the contracts awarded by ESRF. Both the contract values and share of contracts peaked in 2016 and in 2018, both of which are likely to be attributable to procurements for the Extremely Brilliant Source (EBS) upgrade project.

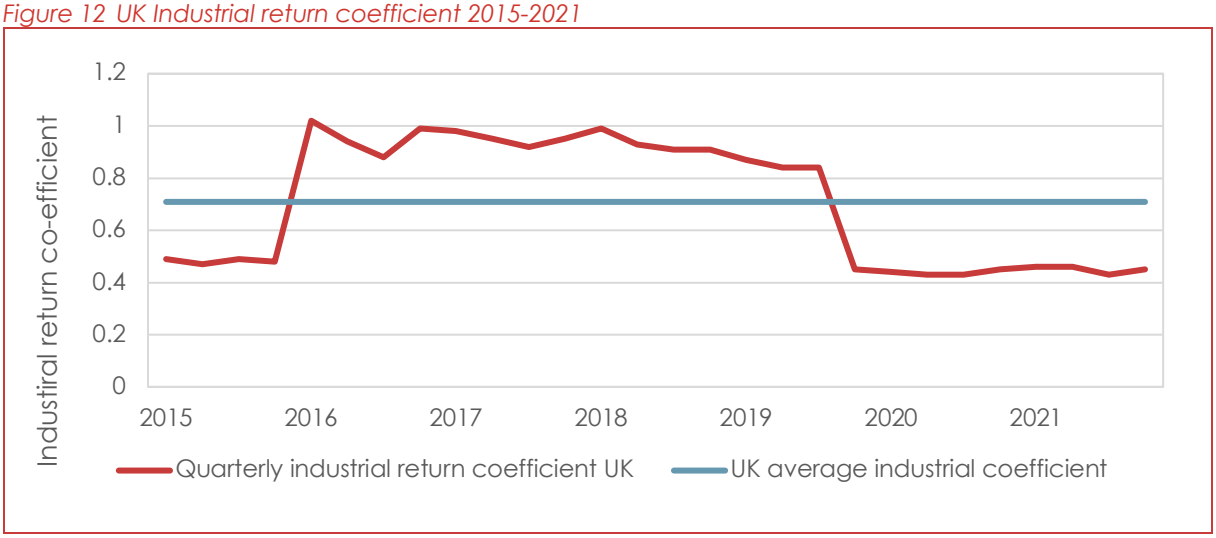
*Figure 11 Comparison of UK supplier contracts over time, and their share of all ESRF contract value*




Source: ESRF monitoring data

These peaks in activity have also helped give the UK a good industrial return from the facility (how the UK's share of contracts corresponds to its shareholding). An industrial return of 1 indicates that the share of eligible supplier contracts (by value) is equal to the share of investment in the facility. As shown in Figure 12 below, the UK industrial return in both 2016 and 2018 were either close to or just above 1, indicating that its share of contracts has broadly corresponded to its overall shareholding in the facility. Over the entire period shown, the UK's rate of industrial return averaged at just over 0.7 per quarter.

*Figure 12 UK Industrial return coefficient 2015-2021*




Source: ESRF monitoring data. Quarterly coefficient presents a rolling multi-year average

Feedback from suppliers suggests that there have been some further economic benefits associated with at least some of these contracts (beyond the value of the contract

themselves). For instance, individuals spoke of how their business would not exist were it not for the contracts they previously secured through ESRF, or how the contracts had helped secure further sales from non-ESRF customers. New markets have also emerged overseas (including other international research institutes), with ESRF contracts helping to create further export opportunities for UK businesses.

**Benefits to UK suppliers – Tesla Engineering Ltd**

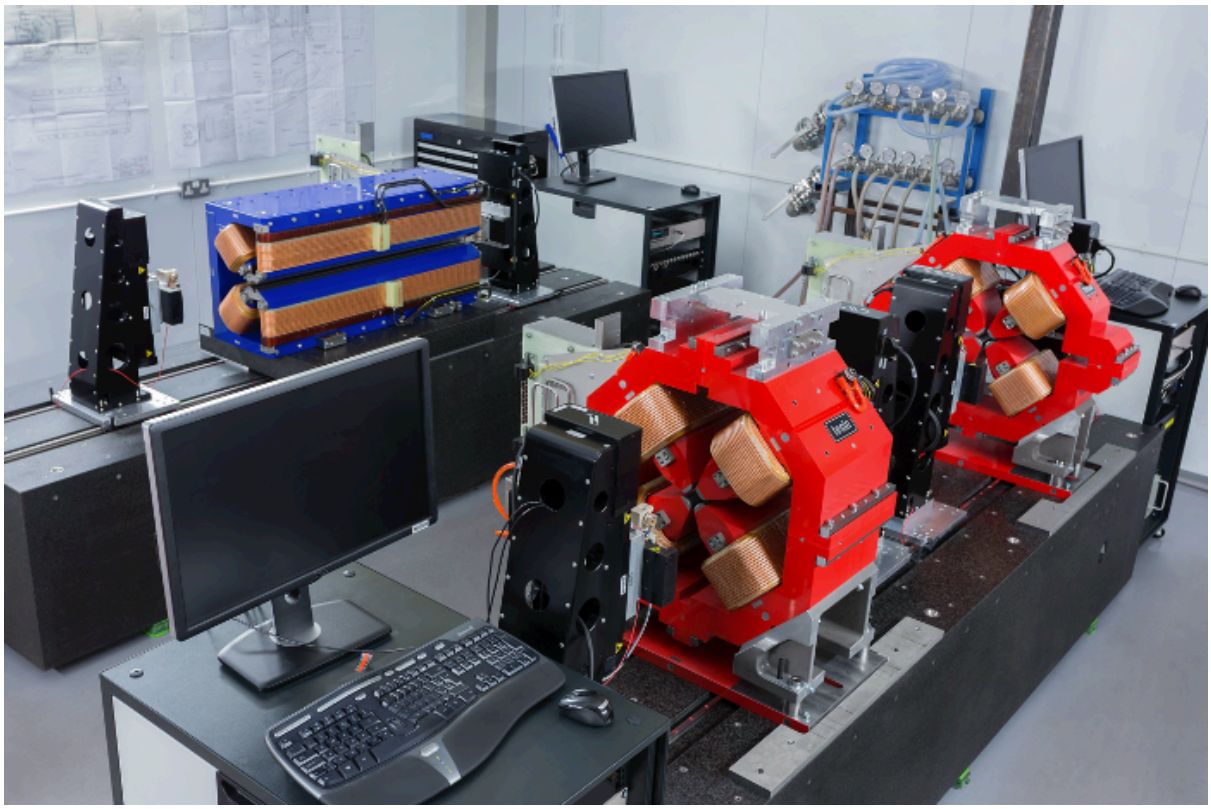
**Background**

Tesla Engineering Ltd is a Storrington-based company supplying electromagnets, gradient coils, composites, motors and consultancy to global science, medicine and industrial markets. Its main ESRF involvement came in the mid-2010s, securing multi-million-euro contracts over a 2-3 year period to design, manufacture, and test magnets as part of the EBS upgrade.

**Benefits seen**

Company representatives have highlighted a number of different ways in which Tesla has benefited from its ESRF contracts:

- Enabling investment in machinery: for ESRF contracts, the company needed to machine in-house high precision magnet yoke assemblies. This required investment in new, latest technology machinery which Tesla has been able to use to help service other contracts (e.g. for radiotherapy treatment machines).
- Developing a track record: ESRF was one of the first facilities to undergo an upgrade in recent years. The facility was demanding in the magnet performance they were looking for. Tesla responded by developing new machining procedures to achieve the requirement from ESRF. The company now has a proven track record in delivering complex services to a high-profile client – something which they can use not only to secure further contracts in the UK but also worldwide.
- Enhanced technical capabilities in magnet testing: As part of the ESRF contracts, the company performed magnetic testing of all the magnets supplied. Using the new magnet measurement equipment enhanced the companies' technical abilities in this area which has been leveraged to win more contracts.
- Employment benefits: Tesla increased its headcount to service the ESRF contract providing jobs for people in the local area, and they believe there has been a benefit to their UK-based suppliers too.
- Company growth: the ESRF contracts has helped grow the company's profits at a quicker rate than might have been the case otherwise enabling further investment.



Interviewed stakeholders also spoke about how UK ESRF suppliers have developed the skills and capabilities needed to supply the future Diamond II, particularly with regards to software, optics, and the design of magnets. In this respect, work for ESRF has helped open up future commercial opportunities for UK suppliers (as well as supporting the successful development of this proposed new facility, using local skills and capabilities). Elsewhere, stakeholders spoke of how very fast X-ray cameras which the STFC's Rutherford Appleton Laboratory has sold to ESRF, are now flowing into other commercial product areas such as electronics.

**Benefits to UK suppliers – AMF Precision Engineering Ltd**

**Background**

AMF Precision Engineering is a Wirral based precision engineering company which offers expertise in areas including parts of aircraft and subsea vehicles, ultra-high vacuum components for the semiconductor sector, and cryogenic, mass spectrometry and equipment for research facilities. Prior to working with ESRF, the company's work primarily centred on cryogenic mass spectroscopy for medical devices.

ESRF appointed AMF to supply crucial mechanical components for ESRF's Extremely Brilliant Source project. Worth €860k, AMF's contract involved providing the mechanical parts of the longitudinal magnets in EBS.

**Benefits seen**

Company representatives have spoken of a number of benefits that their work with ESRF has provided.

- Financial benefits: Work for research facilities is typically 5% of AMF's business. However, when there is a large project for a research facility, such as the EBS work for ESRF, this can increase to 15-20% in a given year

- Exposure to new clients: the research facility market is one that the company is looking to grow. The work for ESRF has provided a basis for this. It for instance enabled them to deliver an exhibition to scientists at ILL, also based in Grenoble; and give a talk at STFC's Daresbury Campus about their work at ESRF. The quality of the components produced coupled with the reputational benefits associated with working for ESRF has also helped AMF secure contracts with other science facilities worldwide, such as Diamond Light Source, ILL and CERN. AMF also secured follow-on contracts with ESRF itself.
- Benefits for the supply chain: as a company, AMF tries to keep as much of the processing work in the UK as they can. To that end, a contract as large as the one they had for EBS helped to create further work for UK subcontractors too
- Investment in new infrastructure: To deliver on ESRF's quality requirements, AMF invested in state-of-the-art manufacturing and inspection equipment.

## 7.4 Other benefits generated

In the main, consulted suppliers have seen the main impact of their contracts being the commercial income they have secured, albeit in a number of cases, ESRF has only represented a small proportion of annual total revenue. Nevertheless, consultees have also highlighted some further benefits of relevance:

- **Skills**: Some ESRF suppliers have also spoken of how there have been some skills development opportunities that have come through their work for ESRF. In some cases, this has centred on gaining experience in new software platforms. For others, ESRF's desire to use new cutting-edge technologies and solutions has in turn encouraged them to push their knowledge and skills into areas they have not looked at before.
- **Creation of new international market opportunities**: some consultees spoke of how working for ESRF helped give them greater visibility with other facility users (including other synchrotrons around the world) and could serve as the basis for future marketing activity. ESRF contracts could also help provide the experience and track record needed to secure contracts to support other facilities too.
- **Opportunities for UK supply chains**: one consultee spoke about how they tried to keep as much technology processing work as possible in the UK, only using sub-contractors abroad where there is no-one locally who can perform the same job.

# 8 Commercial and economic impacts from users

Users have generated economic impacts, both on a micro level in terms of new products and revenue being generated, but also at a macro level in terms of employment in the UK.

## 8.1 Summary

- A wide variety of non-academic organisations have used ESRF, including pharmaceuticals, public energy agencies, chemicals companies, and engineering firms. They have commonly used the facility to undertake fundamental research to help inform the development of new products and processes.
- There are examples of university spinouts emerging from academic research undertaken at ESRF. A notable example is the UCL spin-out, Finden, which now employs ten people.
- There are other examples of UK academic research at ESRF being transferred or licenced out to industry too.
- At a macro-economic level, ESRF has played an important role in helping create and retain high added value jobs. It has also helped attract skilled engineers and scientists to the UK.

## 8.2 Usage of the facility by industry

Data are not systematically collected on the number of industry users that have accessed ESRF, nor the number of academic users that are conducting research on behalf of, or in collaboration with industry. However, based on an analysis of the email addresses of ESRF public beam time UK users over the last ten years, we can estimate that approximately 5% (57 of 1,213) have come from outside the academic community. These non-academic users have come from a wide variety of different organisations including pharmaceuticals, public energy agencies, chemicals companies, and engineering firms. In reality, we anticipate there being even more researchers that have undertaken work with a commercial angle, as described in the section below. In further cases, academics will have also used the research findings from ESRF work to help secure industry funding for further or follow-on work.

Feedback from stakeholders and users indicates that many industry users have used ESRF to undertake fundamental research, including on aspects associated with catalysts and paint properties. To that end, research does not necessarily directly feed into product lines or new manufacturing processes, but may help inform them and support future economic impact.

## 8.3 Commercial benefits achieved from users

There is some evidence of UK commercial benefits emerging from research taking place at ESRF. An example is Finden Ltd, providers of analytical and consultancy services with respect to measurement. Further details are included in the vignette below.

**Finden – a spin-out formed from research at ESRF**

**Background**

Finden is a start-up launched by researchers from University College London in 2012. According to company representatives Finden was founded as a response to growing industry demand for services that were proving too difficult to meet through the university.

Finden provides measurement services utilising various methods, such as microscopy, diffraction, spectroscopy and gas analysis.[31] Finden's value proposition is not just in

[31] https://www.finden.co.uk/about/ (accessed 10 January 2023)

measurement, but also in data interpretation, allowing the team at the company to offer advice to companies, related to the extracted data (i.e., measurement strategies for projects).

**Commercial benefits seen**

Finden has since grown and now has eight full time employees. Finden as a company has itself used ESRF to conduct research too. Company representatives have spoken about the research here having enabled them to develop some intellectual property concerning the screening of large volumes of data, which will serve as the basis for commercialisation opportunities and future business growth as the company looks towards being less reliant on grant funding. The firm has also filed patents based on measurements and data conducted and collected at ESRF. Finden employees are also using their experiences of conducting research at ESRF to sell training courses to those wishing to conduct independent experiments.

More broadly, we have come across other instances where UK academic research at ESRF has been commercialised by others, leading to new products being developed. A number of academic user interviewees and survey respondents have spoken of how they have undertaken work at ESRF in collaboration with industry partners, or that their work has subsequently been passed on to industry partners for further study. Examples include:

- Research into surface science, particularly liquids on solids, which organisations in manufacturing, health and safety, food, and energy have decided to use
- Research into how vision functions in fruit flies, which has subsequently been commercialised into vision systems for drones

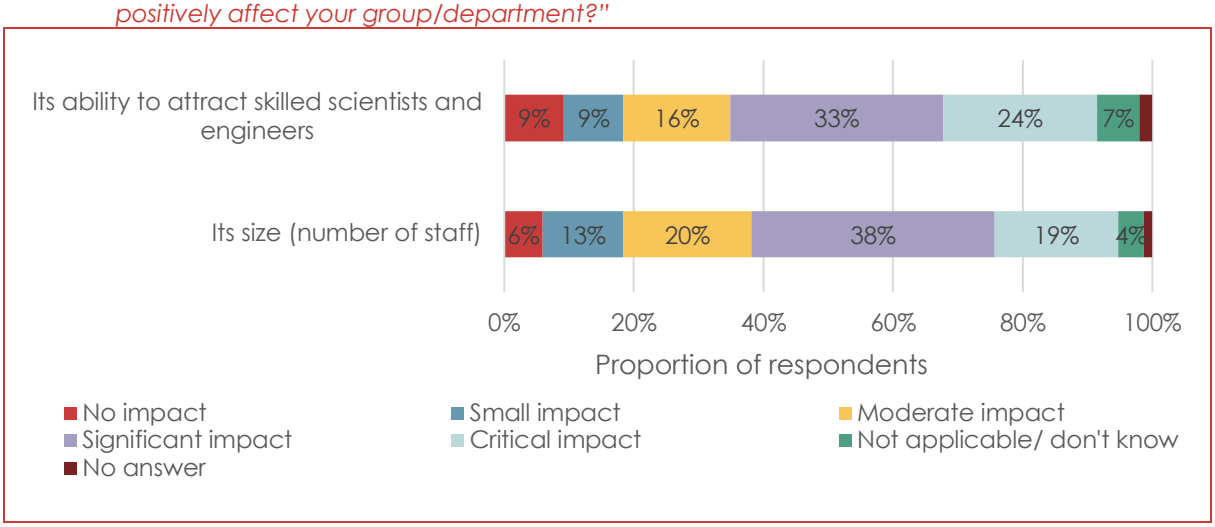
## 8.4 Impacts on the wider UK economy

While some users, both academic and industrial, have clearly seen commercial impacts from their work at ESRF, access to ESRF also appears to have generated wider macro-economic benefits for the UK, specifically in relation to employment. As shown in Figure 13 below, a large proportion of respondents to our survey of UK users believe that ESRF access has played an important role in enabling employment within their research group or department. Over half (57%) said that ESRF had had a 'significant' or 'critical' impact on the number of staff they had, while another 57% said the same of their ability to attract skilled scientists and engineers.

Survey and interview evidence helps provide some indication as to how ESRF may have enabled these employment gains, with respondents for instance speaking of how ESRF-based research had helped secure follow-on funding (which could be used to recruit additional research staff), and the fact that ESRF enabled high profile and cutting-edge research which potential recruits want to participate in.

The results, however, should be treated with an element of caution. There is no evidence to suggest that all of this cited employment will be additional, and one would certainly expect a certain level of deadweight and displacement. Nevertheless, it would be reasonable to expect at least some level of additionality associated with the employment generated.

*Figure 13 User survey responses to "To what extent does UK membership of/involvement in ESRF positively affect your group/department?"*




Source: ESRF user survey (n=152)

# 9 Summary and conclusions

## 9.1 The UK's involvement in ESRF

- The UK was a founding member of the ESRF in 1988. It now contributes (through STFC) approximately 10.5% (c.€9.5 million)[32] of ESRF's annual budget, making the UK the fourth biggest financial contributor to the facility and providing a wide range of UK scientists, engineers and business (as well as wider stakeholders) with additional opportunities
- The UK's involvement in ESRF has generated benefits to the UK in the following areas:
  - Scientific and research benefits
  - Skills benefits
  - UK policy and wider strategic objectives
  - UK's international standing
  - UK benefits from supplying the facilities
  - Commercial and economic benefits

  The main findings of the study in each area are summarised in the sub-sections below.

## 9.2 Science and research benefits

- The UK's usage of ESRF has been in line with its shareholding. It is one of the facility's heaviest users, with only three other countries (all of whom have higher shareholdings) having used it more over the last ten years.
- The UK has also formed a collaborating research group (CRG) via EPSRC, which has operated the XMaS (X-ray Magnetic Scattering) beamline at ESRF since 1997. The CRG can prioritise access to beamlines for UK researchers, while also being used more widely.
- ESRF supports a diverse range of disciplines in the UK. Having previously been used primarily by physicists, the facility has become increasingly important for users in other science and non-science research areas.
- ESRF has also supported the UK in producing high quality research, with its share of research publications linked to ESRF usage also being higher than its shareholding. Some 80% of these UK publications have been multi or interdisciplinary, a level higher than would typically be expected. This again shows the relevance of the facility across a variety of domains.
- ESRF has offered high additionality, given that very few other facilities provide the capabilities that ESRF can. Since the upgrade to EBS, ESRF has been the world's only fourth generation synchrotron. Many users highlighted that in the absence of ESRF, their research projects would simply not have been possible.

## 9.3 Skills benefits

- UK users have spoken very positively of the effects that ESRF usage has had on their own skills, but also those of their wider research team. In particular, they have cited how having access to high quality staff working at ESRF has helped improve their knowledge of how to use different instruments, and indeed how to work at other research facilities.

[32] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/460406/EM_Prot_Russ.pdf (accessed 6 September 2022)

- The strong international focus of ESRF has also been helpful to UK researchers, allowing them to interact with and learn from a diverse range of researchers, as well as improving their abilities to work in international environments, and in international teams.
- Users spoke of how UK PhD students and other early career researchers have benefited the most in terms of skills improvement through ESRF access, by giving them hands-on experience on experiments that would ordinarily be difficult to conduct elsewhere, and in providing access to people that they might not meet in the UK.
- A number of UK school-aged students have also benefited from the successful and well-regarded XMaS Scientist Experience scheme which has helped encourage young females to pursue science-based careers.

## 9.4 UK policy and wider strategic objectives

- The UK's involvement in ESRF has led to spillover benefits to Diamond and other UK research facilities, most notably by providing experience, technologies, and best practices that can inform the development of other UK research infrastructures such as Diamond II, as well training staff that later have gone on to work at such facilities.
- ESRF has also played a role in helping STFC meet its strategic goals to strengthen the UK's research and innovation community, particularly in relation to early career researchers and access to international networks and opportunities
- The UK's interactions with ESRF have helped contribute towards some long-standing wider policy priorities for the UK including:
  - Producing the technologies that will help decarbonise the economy
  - Supporting businesses based outside the south-east, helping with levelling up
  - Supporting SME growth, by providing them with contract opportunities at the facility
  - Helping fulfil aims to become a science superpower by 2030

## 9.5 The UK's international standing

- Access to ESRF has given the UK greater resilience and security in accessing leading scientific research facilities.
- There are soft power gains for the UK too, with its involvement in ESRF ensuring it maintains influence in international science decision making. It has also helped enhance the UK's reputation as a centre of scientific research, with the UK being able to associate itself with a facility which itself is very highly regarded around the world.
- ESRF involvement has also created international collaboration opportunities. Indeed, levels of international collaboration amongst UK researchers at ESRF have increased over time.

## 9.6 UK benefits from supplying the facilities

- The UK has sold a range of different goods and services to ESRF over the last ten years, spanning from magnets used on the beamlines themselves, to software and control systems, and instruments. A diverse range of suppliers have provided these goods and services including public sector, engineering and manufacturing firms, and software firms.
- Between 2015 and 2021, UK suppliers to ESRF have won contracts worth nearly €16 million. The UK's rate of industrial return (which compares its shareholding with its share of contract value awarded) averaged out at 0.7 over this period.
- The ESRF contracts have also been important in helping UK firms develop the skills and market visibility needed to secure contracts outside ESRF. This expertise will also enable UK firms to supply Diamond II in the future.

## 9.7 Commercial and economic benefits

- While being important for academic users, ESRF access has also benefited other research communities in the UK too. Non-academic organisations such as pharmaceuticals, public energy agencies, and engineering firms have all undertaken fundamental research at ESRF, using findings to help inform the development of new products and processes.
- There are also examples of UK researchers forming university spinouts from their ESRF-based research. A notable example is the UCL spin-out, Finden, which now employs ten people.
- In terms of macroeconomic benefits, users have been clear that the ability to work on high-profile and cutting-edge projects via ESRF has helped attract and retain highly skilled researchers and engineers to the UK.

# Part 2: Evaluation Framework

# 10 ESRF future monitoring and evaluation framework

In this chapter we present our proposal for a monitoring and evaluation framework that STFC can use as the basis for tracking the benefits flowing from the UK's involvement in ESRF. The framework is also designed to support future independent evaluations by ensuring that there is a more wide-ranging and complete record of achievements across each of the principal impact pathways.

## 10.1 Design assumptions

The framework draws in large part on the approach adopted for the current study, which has been shown to provide useful and reliable evidence as to the impact that ESRF membership has had for the UK. We have however, simplified and consolidated some of the impact areas, and provided a clearer elaboration of the role for STFC in creating and collating information.

*Table 6 Overall structure for impact areas – benefits from UK investment in ESRF*

| Area | Benefits to UK |
|---|---|
| 1. World-class science and research | 1.1 Pushing the frontiers of human knowledge & understanding, enabling further scientific progress<br>1.2 Sustaining the UK's research excellence & leadership through access and opportunities at ESRF<br>1.3 Supporting the UK's involvement in multidisciplinary and interdisciplinary activity<br>1.4 Attracting investment & talent via improved perceptions of the UK as a leading research nation |
| 2. World-class skills | 2.1 Increased skills and capabilities of the UK workforce<br>2.2 Increased (future) UK STEM workforce |
| 3. The UK's international standing | 3.1 The UK's influence in the international science and technology landscape<br>3.2 Improved diplomatic relations and engagement<br>3.3 The UK's image as a 'great science and innovation nation'<br>3.4 The UK's ability to engage with and/or lead international research collaborations |
| 4. World class innovation | 4.1 UK benefits from the wider application of ESRF-derived technologies<br>4.2 UK benefits from wider application of ESRF-supported research<br>4.3 Spillover benefits to other UK research facilities<br>4.4 Increased performance amongst UK suppliers to ESRF |

We have assumed that the framework will support STFC in monitoring the full extent of UK involvement with ESRF, to facilitate enhanced operations on the one hand, and more extensive annual reporting on the other. It should also provide an improved platform for future evaluations, allowing evaluators to concentrate on analysing the range of additional wider benefits attributable to ESRF involvement, and less on basic data collection and compilation.

In developing this framework, we have also reflected on our experiences of undertaking this study, and in particular some of the methodological limitations and constraints faced. A notable methodological deviation from this framework and our study is the use of a list of ESRF suppliers rather than the STFC CRM used for this study. Owing to resource constraints at ESRF, and time pressures associated with the study, we were unable to obtain a full list of UK-based suppliers to ESRF as well appropriate contact details from them. As such, the suppliers survey was not as well targeted as it may have been, and the survey may not necessarily have reached all of the intended audience. We expect that STFC will have greater time to establish the relationships needed with ESRF to obtain the required supplier details from them, and thus ensure that future monitoring activity has better quality evidence it can draw on.

Another key consideration in the development of this framework is the feasibility of the data collection requirements. While we acknowledge that the framework is an ambitious one, we also believe it is a realistic and achievable one should a reasonable level of resource be

available to STFC. Nevertheless, we appreciate resource levels may be uncertain going forward and have therefore highlighted the indicators that STFC should prioritise for collection.

## 10.2 The Framework

The following tables present lists of possible indicators against the four impact areas and 14 pathways set out above. The implementation column discusses where the data may be sourced from and by whom. It also includes various suggestions for measures to strengthen the STFC-ESRF monitoring system in order to provide future evaluations with a more comprehensive and robust evidence base. The list of performance dimensions is shorter and simpler than that explored in the current evaluation, reflecting lessons learned about information availability, what is important for understanding ESRF's key contributions, and what is feasible within the context of a typical, broad-ranging evaluation (covering all impact pathways) such as this.

*Table 7 ESRF monitoring and evaluation framework: proposed indicators for world-class science and research*

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| 1.1 Pushing the frontiers of human knowledge & understanding, enabling further scientific progress | Annual presentation (list / case studies) of notable scientific and technological advances | • STFC already seeks to identify and showcase notable scientific and research advances realised through ESRF involving UK-based scientists. While key individuals are aware of this list of examples, it is not captured in a systematic or consolidated manner<br>• STFC should look to maintain a list of notable examples, updating on an annual basis. The list of case studies presented for this study could act as a starting point.<br>• These individual items could provide the basis for the development of longer and more structured 'scientific advances' case studies, developed periodically either by STFC or by external contractors. The ambition should be to produce 4-5 scientific case studies a year out of a longer list of promising items<br>• This portfolio of cases should be developed to reflect STFC's strategic commitment to both (i) frontier research and (ii) its underpinning technology. They should also present not only the research result, but also say more about the significance of its implications for wider science (and ideally also for wider society and the economy). | Annual |
| 1.2 Sustaining the UK's research excellence & leadership through access and opportunities at ESRF | Number of UK researchers accessing ESRF facilities | • Annually, STFC should work with ESRF to obtain and collate statistics on the number of UK users, and the number of UK researchers associated with the facility. Where possible, this should include the amount of beamline time requested and awarded to UK-based researchers, at a beamline level<br>• Information on other Member States (if available), or at least on all countries combined, would provide a useful benchmark. | Annual |
| | Bibliometrics<br>– Annual number (and UK share) of publications on ESRF research<br>– Share of UK papers in the 10% most highly cited papers that have used ESRF<br>– Annual number of publications citing ESRF papers, UK share | • The engineering and physical sciences make extensive use of journal articles, and as such bibliometrics provides an efficient means by which to track the volume of UK-related ESRF research outputs and assess its international standing.<br>• The analyses might be kept very simple, such that STFC could run the analytical exercise internally every year using an online platform and based on the list of publications citing ESRF that ESRF itself records centrally. Otherwise, there are a number of firms providing bibliometric analytical services reasonably economically. Such services could be contracted, perhaps alternating from one year to another between a simple computation of three or four standard citation metrics and a more wide-ranging analysis of the UK's international standing in various disciplines in comparison with benchmark countries.<br>• The in-depth bibliometric analysis could also seek to capture references to ESRF research in other disciplines, reflecting its influence in other areas of research. | Annual |

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| | List of UK-based scientists / engineers that have won major scientific prizes in recognition of ESRF research | • STFC is already tracking prizes, some of which are showcased in the STFC Annual Impact Report.<br>• This could provide the basis for an ESRF-specific account of prestigious awards, which could be reported in a separate paper as well as being picked up as appropriate in corporate publications. | Annual |
| 1.3 Supporting the UK's involvement in multidisciplinary and interdisciplinary activity | Proportion of all papers citing ESRF and involving UK authors, that cover more than one subject area or topic | • The methodology used in this study could be replicated every 3-4 years to help show the progress made against this indicator<br>• STFC should work alongside ESRF to obtain a list of the DOIs of academic papers involving UK authors which have cited ESRF. These can then be combined with subject/topic categorisations of each paper, as provided in LENS.org, which can be used to determine whether papers have covered multiple topics or not<br>• This analysis could also examine which subjects collaborate with each other the most<br>• This is a labour-intensive exercise and therefore should occur on an infrequent basis. It may also be best done by external contractors | Every 5 years |
| 1.4 Attracting investment & talent via improved perceptions of the UK as a leading research nation | List of international researchers locating in the UK to take advantage of UK strengths relating to ESRF | • STFC may be able to orchestrate this monitoring activity, drawing on its pre-existing network of contacts in key institutions.<br>• This would involve STFC engaging annually with a shortlist of (~15) individuals from the stakeholder community with a good view of the UK's involvement overall with ESRF (e.g., representatives from key university departments and laboratories).<br>• This could take the form of an interview or feedback form, requesting examples of notable investments, inward movement of researchers, and the latest developments in their field. Indicative examples could then be pursued for further detail as necessary. | Every 2-3 years |

*Table 8 ESRF monitoring and evaluation framework: proposed indicators for world-class skills*

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| 2.1 Increased skills and capabilities of the UK workforce | UK-based researchers and students' participation in ESRF-related activities | • An annual report should be produced, presenting an overview (count) of the UK population conducting research at or working with ESRF. ESRF itself is able to provide this data, and understand that they may be able to provide data on UK staff employed at ESRF.<br>• STFC should also monitor the number of UK students involved in internships and training schemes at ESRF, run either centrally by the facility itself, or by XMaS | Annual |

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| | | • Determining the impact on skills will require additional work to systematically and routinely poll researchers on the skills and social capital they acquire through their work at/with ESRF, e.g. looking at a range of domain, technical and management skills. Group leaders could also be asked how many PhD theses have been delivered with ESRF as a central focus/data source, and how many PhD students are working on ESRF projects<br>• It will also be useful to establish a career tracking capability to begin to follow the progress of ESRF alumni through their future careers, across job titles, sectors and borders. This may be tackled best in collaboration with ESRF | |
| 2.2 Increased (future) UK STEM workforce | Engagement of students with ESRF | • STFC should work with EPSRC to compile and present an annual statistical review showcasing the numbers of schoolchildren visiting or using ESRF as part of XMaS' Scientist Experience.<br>• They would also benefit from a follow-up survey to determine whether attendees have chosen science subjects at university and/or are more likely to consider a career in science or engineering | Annual |
| | Impact on student subject selection | • STFC should consider developing a STEM uptake observatory, which would run periodical studies of students to track their engagement with ESRF (and other similar facilities) and their views on science and their choice of subjects, higher education decisions and careers. | Every 5 years |

*Table 9 ESRF monitoring and evaluation framework: proposed indicators for the UK's international standing*

| Impact pathway | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|
| 3.1 The UK's influence in the international science and technology landscape | • A chapter could be included within an annual STFC report, detailing notable developments and more generally itemising all such highlights (through ESRF and other facilities).<br>• The material would need to be identified internally within STFC, via researcher surveys and through discussions with ESRF and those UK individuals in key positions with ESRF (e.g. representatives on the Council or committees). Occasional examples could be highlighted in the annual report, while the most promising could be prepared into fuller science diplomacy case studies | Annual |
| 3.2 Improved diplomatic relations and engagement | • STFC could develop a tool for inviting its scientific partners to provide feedback on the experiences of collaborating with UK-based scientists. This could help understand areas where the UK is strong or less strong is, and where STFC could provide training or encourage different behaviour. | Every 2-3 years |

| Impact pathway | | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| | | • To obtain a more rounded view of perceptions, STFC will need to commission international research to determine the views of scientists, scientific administrators, professionals and the public in ESRF member countries. This is the type of work could occur alongside the science and innovation councillors in the UK embassies. However, it may be too burdensome for them to implement fully, making the appointment of a consultant a better option.<br>• Data collection will also need to be done at sufficient scale to allow the analysis to test for links between UK work at ESRF, and perceptions of UK science more generally, perhaps through selected critical incidents. | |
| 3.3 The UK's ability to engage with and/or lead international research collaborations | Number of UK-authored academic papers that cites ESRF which also involve international collaborators | • ESRF's publication database already contains the nationality of all authors. This should be analysed on an annual basis<br>• Similar analysis should occur with publications that have authors from another country to help provide a benchmark | Annual |

*Table 10 ESRF monitoring and evaluation framework: proposed indicators for world-class innovation*

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| 4.1 UK benefits from the wider application of ESRF-derived technologies | List / case studies of technologies developed at or for ESRF, which have come into wider use | • STFC should look to produce a list of relevant technologies (with wider application) and update this annually. This should include new additions in the past 12 months, and a longer list of previous success (the stock).<br>• This could draw on several sources, including Gateway to Research, a survey of ESRF suppliers (which could be based on the one developed for this study), and work that STFC does more generally in tracking achievements (as set out in 1.1).<br>• STFC should also develop one or two examples into fuller impact case studies each year, exploring the wider benefits to the UK. They could then disseminate these via social media platforms. | Annual |
| 4.2 UK benefits from the wider application of ESRF-supported research | List / case studies showcasing the application of ESRF research, which has come into wider use elsewhere | • STFC should keep under review any news about the application of ESRF research in other areas of relevance to the UK, such that it might develop one or two impact case studies annually.<br>• These cases may need to be prepared – or at least approved by the affected UK-based researchers and should therefore follow the structure of Research Excellence Framework (REF) 2021 case studies to minimise any burden on the research community. | Annual |

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| | | • A long list of candidate cases might best be prepared based on several sources, including a new researcher survey, as well as the work of STFC in tracking UK achievements at ESRF more generally. REF 2021 submissions may also provide a useful starting point. This exercise might be accompanied by an examination of the wider use of UK-based ESRF research in other fields / countries (using bibliometrics). | |
| 4.3 Spillover benefits to other UK research facilities | Knowledge transfer between ESRF and Diamond | • STFC should look to engage with key contacts and senior stakeholders at Diamond each year, using this as the basis to compile a list of the main areas of interaction between the two facilities, and the key outcomes from this<br>• STFC may also want to co-ordinate an annual survey of all new staff at Diamond to determine if they have previous work or research experience at ESRF too<br>• It may also be beneficial to incorporate as part of any bibliometric analysis, an examination into whether Diamond staff and ESRF staff have co-authored research papers together<br>• While data may be collected on an annual basis, analysis could get place every 4-5 years, recognising the effort it may take to obtain this information | Every 5 years |
| 4.4 Increased performance amongst UK suppliers to ESRF | List/value of products / services brought to market by UK firms which stem from work carried out for ESRF | • ESRF already collects data on UK-based suppliers that it contracts, and the value of contracts awarded. STFC should work with ESRF to gain access to up-to-date figures on these aspects each year<br>• STFC may wish to supplement this with a biennial survey of suppliers, using contacts provided by ESRF, to determine the employment and revenue effects of ESRF contracts. Drawing on contacts provided by ESRF may yield better response rates than drawing solely on STFC's CRM system. | Every 2-3 years |
| | International competitiveness of UK-based suppliers to ESRF | • STFC might want to carry out a biennial analysis of the competitiveness of UK-based suppliers, to determine if ESRF contracts have helped them secure contracts with other facilities, and helped them bring new products to market (and any turnover or employment associated with it)<br>• This exercise is more involved than simply tracking sales and employment and does need additional primary data on exports and profitability. It also requires some level of econometric analysis to take account of different contractual histories and also to allow for a comparison of ESRF suppliers with the performance of matching groups of firms in order to estimate the size of any statistical differences. | Every 2-3 years |
| | UK industrial return in goods and services | • ESRF already collects data on contract awards and industrial return co-efficient, including for the UK. STFC should work with ESRF to obtain data updates on an annual basis. STFC can use this to gain trend data, as well as enabling comparisons with other countries | Every 2-3 years |

| Impact pathway | Indicator | Implementation (who, what, how) | Frequency of data collection |
|---|---|---|---|
| | | • More fine-grained information on individual contracts (and contractors), as well as unsuccessful bids would also offer further insight. This level of detail should be available from ESRF on request<br>• There would however be merit in doing more: a more disaggregated analysis in order to inform STFC as regards the effectiveness of its various promotional efforts (analysing bids too, if possible, as well as contract awards). STFC will no doubt want to continue its efforts to raise awareness among prospective bidders and may also want to trial new approaches such as producing more success stories to show businesses that contracts are winnable and can deliver benefits even with low margins, or more proactively sharing tenders with CRM members.<br>– A fuller, sector-specific analysis, would allow STFC to determine the relative effectiveness of its various business development efforts. A survey of suppliers could also provide feedback on company experience of the contracting process, STFC support and views on 'best practice' or 'lessons learnt' to share with organisations interested in bidding. | |
| 4.5 Commercialisation of research | Generation of intellectual property following research undertaken at ESRF | • We understand that STFC already plans to use Researchfish data to collect information on patents, copyrights and trademarks that have been created as outputs of research they have supported.<br>• STFC should look to capture this information on UK research conducted at ESRF, working with the facility as needed to secure any additional information needed. | Every 5 years |
| | Spin-out activity | • We understand that STFC is also planning to capture spin-out companies initiated as outputs of STFC-supported research as part of its benefits and realisation framework. It will look to use Researchfish data for this.<br>• STFC should look to capture this information on UK research conducted at ESRF, working with the facility as needed to secure any additional information needed.<br>• STFC should look to capture not only the number of spinouts initiated, but the number of STFC staff employed as a member of the company. | Every 5 years |

The framework presented above points to the need for several **additional data collection activities**, including new surveys (e.g. of UK-based ESRF suppliers), bibliometric analyses and the collation of examples of technology development. These additional activities (discussed further below) could constitute part of an enhanced monitoring system, run on a continuous basis by STFC or contractors, and informing operational oversight and periodical evaluations.

## 10.3 Monitoring arrangements

In addition to continuing the current monitoring and reporting arrangements, including working closely with ESRF to determine what relevant information they are able to share, we recommend STFC considers implementing **several additional data collection / analytical activities** to strengthen the monitoring system.

- Researcher survey: Implement an annual or biennial survey of all UK-based ESRF researchers (which might be targeted just at PIs awarded beam time), to obtain feedback on notable achievements in each of the four impact pathways.
- Supplier survey: Implement an annual or biennial survey of UK-based ESRF suppliers to obtain feedback on their experience and capture information about specific capability benefits, innovations, wider sales and exports, plus competitive advantage. This exercise could be extended to all applicants (successful and unsuccessful) and seek to capture wider insight and feedback or focus just on those awarded contracts. In either case, requesting information on specific applicants / contractors from ESRF, rather than relying on STFC's more general CRM, might improve response rates.
- Outreach programme beneficiary survey: Implement an annual survey where EPSRC or STFC contacts those participating in the XmaS Scientist Experience a year after completion. This should be short survey that asks how they have used knowledge gained through the programme, what subject they plan to study at university, and their thoughts about pursuing a future career in science or engineering
- Engaging with Diamond stakeholders: We recommend an annual consultation exercise with Diamond stakeholders to help identify the various ways that Diamond and ESRF have collaborated with each other. These should be recorded in single repository, which also set out the relevant impact pathways that the example covers. This repository can be drawn on as needed, with particularly noteworthy examples being used as part marketing and communications activities. Stakeholder engagement might also involve a short survey every year of new joiners to the Diamond staff base, to help determine whether they have previously worked at or with ESRF, either as part of their academic training, or as an employee of the facility.
- Cataloguing individual achievements: There are numerous instances of individual successes in each of the four impact pathways, and STFC and ESRF are already capturing some of these, albeit in an ad hoc and unsystematic manner. It would be helpful, however, if STFC could broaden its search for notable achievements. The current arrangements mostly capture information about scientific advances, but there is likely to be more to report on industry and skills and working systematically across all four impact pathways may be helpful. It would be good to record all of these items in a single repository or database, tagged with the relevant impact pathways and performance dimensions. This would produce a much longer list of interesting facts than can be presented in an annual report or newsletter, showcased in rolling communication activities, as well as support further analysis and feed into future evaluations.
- Case studies: STFC should then identify and develop a selection of examples from each impact area into fuller case studies, based on additional discussion and desk research.

These cases could aim for two pages (500 words plus images) and follow a reasonably standard structure (from ESRF-related activities, through the outputs and outcomes of this work, on to potential/realised wider socio-economic benefits). The resulting cases could then be used in a number of different ways, to support STFC annual reporting and periodical external evaluation of UK participation in ESRF.

- Biennial review of UK science at ESRF: There would be benefit in carrying out regular bibliometric analyses to gauge the international standing of UK-based scientists on the one hand and the citation of their work on the other. This would also allow STFC to understand the changing geography of UK cooperation and selective international benchmarking with other leading scientific countries. It would also enable an assessment of the level of international collaborations occurring, as well as the amount of multi and interdisciplinary research occurring.

We understand that STFC is currently developing a benefits and realisation framework to use across its entire portfolio of work. There may already be plans to incorporate some of the elements above into this, but STFC may also need to undertake a mapping exercise to determine whether any of these activities need adding to the planned framework.

## 10.4 Assessing the counterfactual

Assessing the counterfactual is always difficult when examining the impact of research infrastructures such as ESRF. The facilities tend to cater for relatively small and niche areas of the scientific community, meaning that there is not a large pool of well-matched non-users which could form a robust control group. An alternative counterfactual approach could be to study the outcomes and impacts generated at other research facilities that UK researchers use, using this as a basis for deciding whether the UK is getting more out of ESRF than it could do otherwise. However, there are few comparable alternatives to either facility that could be used for this basis. Furthermore, our research has found that many users use alternatives alongside ESRF rather than instead of it. To that end, it was not practical to separate facilities into control or treatment groups given the significant overlap of users between them.

Consequently, we suggest that future evaluation activity relies on self-reported additionality. This is an approach that has worked well in this study – consultees have been able to gain insightful comments from users and suppliers alike to more qualitative questions around the difference the facility has made to them, and what (if anything) they might have been able to achieve without the facility. This approach, is used in the framework too, will be in keeping not only with this study, but also with other previous impact studies of research infrastructures, including Technopolis' 2021 impact study of Diamond Light Source.

## 10.5 Evaluation arrangements

The experience of conducting the current study has uncovered gaps in evidence and research/analysis methods to support a holistic, robust assessment of ESRF's impact on the UK. A strengthened STFC monitoring system that focuses on documenting activities, outputs, and outcomes will help with this. The evaluation itself should be able to build on this improved monitoring system, corroborating data and extending the benefits-realisation perspective to the wider effects on science, innovation and skills. It should also be able to identify, quantify and monetise more of the total spectrum of ESRF benefits than was possible with this evaluation.

The framework will enable a more systemic monitoring of the quantum of benefits achieved under each impact pathway whereas this study has had to rely on the view of stakeholders and degree of serendipity to find high impact examples (meaning that our analysis may have missed some notable examples that consulted stakeholders are not aware of). The framework also incorporates additional quantitative analysis such as bibliometric analysis which was out of scope for this study. This framework will therefore move the evaluators closer to being able to carry out a cost-benefit analysis that provides a more complete and fair account of ESRF-derived benefits for the UK.

The timing of future evaluations is a matter for discussion, as there is no clear advice in existing UK evaluation guidelines and the periodicity and scope of the government's comprehensive spending reviews is rather changeable. Historically, the grant-awarding research councils and their research institutes were subject to 5-yearly, or quinquennial reviews, and while this is no longer the case, the periodicity feels appropriate to a major science programme (three years is arguably too short, and 10 years is arguably too long).

# Appendices: Case studies

# Appendix A Human Organ Atlas Case Study

## Summary

The Human Organ Atlas is a University College London led research project which has developed a new methodology, Hierarchical Phase-Contrast Tomography (HiP-CT), to improve the understanding of the human anatomy. It is looking to produce high quality, 3D images of the human body, considering parts of the body from everywhere between the micron level to the whole intact organ level. The study has its roots in a technique developed by the ESRF beamline scientist, Paul Tafforeau, to produce high resolution images of biological specimens. A research team, led by University College London, looked to take this approach and apply it to the human lung, specifically to study the effects of COVID-19 on the organ. The research has been a high-profile project, attracting international attention both inside and outside academia. The project has already improved scientists understanding of the way that COVID-19 damages lungs, and the research team expects it to also inform the treatment of other diseases.

ESRF has been central to the project's success. It was the only facility in the world that could provide a high enough energy source that could penetrate something as thick as an entire organ. The research team has also valued the quality of the staff and sample preparation facilities that ESRF also provides.

## Background

The Human Organ Atlas has its roots in research undertaken by ESRF beamline scientist, Paul Tafforeau, who in 2011, used phase-contrast X-ray techniques to conduct reconstructions of biological specimens. The high energy and spatial coherence offered by ESRF after the EBS upgrade mean that the x-rays produced enables large, intact human organs to be scanned for the first time, with outstanding resolution of soft tissue using propagation phase contrast. Phase-contrast techniques involve studying minute changes in the X-ray phase as it travels through tissues with tiny density changes and the interface, producing 3D images of very high detail and contrast. Paul Tafforeau used this technique to conduct detailed scans inside the skills of the human ancestor, *Australopithecus sediba*, or ancient human teeth, and mummified crocodiles.[33]

In 2020, the onset of the COVID-19 pandemic led to a community of scientists to consider whether Paul Tafforeau's technique on fossils could also be applied to human organs to study the health effects of COVID-19. Led by Peter Lee, at University College London (UCL), a team comprising synchrotron imaging scientists, mathematics, computer scientists, and medical scientists began a collaboration that developed a new technique called hierarchical phase-contrast tomography (HiP-CT), building on Tafforeau's earlier work, to study changes in entire organs.[34] Previously they had only been able to study changes on small organ samples, making it more difficult to consider effects on an entire body.

## The Research Project

As noted above, the research began as an exercise to study the effects of COVID-19 on lung samples during the early stages of the pandemic. Since then, the research has evolved further with it looking to develop detailed images of all organs in the human body, down to individual

[33] https://physicsworld.com/a/the-body-exposed/

[34] Ibid.

tiny blood vessels. To date, the team has studied lungs, the heart, and the brain with results being available on an open-source basis. The ultimate goal is to create a create an online image of organs which allow users to study scales from as large as centimetres and metres, to as small as micro-scale structures.[35]

The research team has also focused on further developing their HiP-CT technique, bringing together a multidisciplinary team that includes medics, biologists, sample preparation specialists, and computing and machine learning specialists.

## Impacts generated

*Scientific and research*

The Human Organ Atlas project has already produced some important findings, having in particular helped to understand the improve the understanding of COVID-19 and long Covid on the body[36]. Using HiP-CT, the research team was able to see how severe COVID-19 infection leads to shunting in the lungs. This is where blood is transported through the lungs without taking part in gas exchange.[37] In particular, the study found that COVID-19 caused shunting in two separate systems: the capillaries which oxygenate the blood, and those that feed the lung tissue itself – both phenomena stop a patient's blood from being properly oxygenated. Researchers had previously hypothesised these effects of COVID-19 on the lung, but use of the HiP-CT technique has helped to confirm it.[38]

Work has subsequently progressed to look at other organs too. To date, researchers have used HiP-CT to create 3D images of a brain, a heart, a kidney, a spleen, and a liver. The hope is that by 2025, the research team will have been able to image an entire human body.[39]

*Commercial and economic*

There has been some research and knowledge transfer to industry too. Peter Lee's research team has been working with the health medical device company, Siemens Healthineers, with a goal of producing better health training tools. The collaboration is focusing on producing better images of organs, in particular, showing the progression of disease in them. This help provide better training tools to healthcare professionals. There is also an ambition to use the images produced through the research to enable a testing of operations in the real world. This is becoming a more important issue in certain areas of medicine, such as child cardiology, where improving mortality rates means that clinicians now have fewer organs to train on. There is an increasing reliance therefore on training in a virtual environment, meaning that solutions such as those that Siemens Healthineers is developing are more in demand.

*Skills benefits*

Consultees have spoken of a number of skills benefits that have resulted from the project. The study's principal investigator highlighted how their research background was in x-ray physics.

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[35] https://physicsworld.com/a/the-body-exposed/

[36] Ackermann, M., Kamp, J. C., Werlein, C., *Walsh, C. L.*...Jonigk, D. D. (2022). The fatal trajectory of pulmonary COVID-19 is driven by lobular ischemia and fibrotic remodelling. EBioMedicine, 85, 104296.

[37] https://www.scottishintensivecare.org.uk/training-education/sics-induction-modules/respiratory-failure-5/#:~:text=Shunt%20occurs%20when%20blood%20is,)%20and%20atelectasis%2C%20fig%203.

[38] https://www.ucl.ac.uk/news/2021/nov/brightest-ever-x-ray-shows-lung-vessels-altered-covid-19#:~:text=Using%20HiP%2DCT%20to%20create%20the%20Human%20Organ%20Atlas&text=This%20will%20display%20six%20donated,a%20Covid%2D19%20lung%20biopsy.

[39] https://physicsworld.com/a/the-body-exposed/

Working on the Human Organ Atlas, including through work led at ESRF, provided them with an opportunity to engage with and work alongside medics more than they ever had done before. The research team has also been multidisciplinary, enabling the cross fertilisation of ideas from different subjects and methodologies. As mentioned previously, the Human Organ Atlas has relied on skills and experience from diverse researchers including medics, biologists, specialists in sample preparation, and experts in machine learning, artificial intelligence, and computing.

The research team has also involved some early career scientists. According to the project representatives, these early career researchers have been put at the forefront of a new field, through their work on the Human Organ Atlas. As a result, they have been able to enhance their reputation and exposure not only within academic circles, but outside it too, by contributing to television and mass publication features.

*UK benefits to supplying the facilities*

Project representatives spoke of how there are likely to be opportunities for data management suppliers going forward, including those from the UK. Current estimates are that the Human Organ Atlas will produce 2 Petabytes of data (equal to 1,000 Terabytes), similar to the amount of data held in Google Earth. To be able to handle and store such a large amount of data, ESRF will need to work closely with specialists in these areas which could create opportunities for UK-based organisations.

*UK's international standing*

The Human Organ Atlas is a project that has gained international traction. The research has for instance featured in major international publications such as *National Geographic* and *Nature Methods*, with researchers also being invited to speak about the work at international conferences.

The project has also fostered international collaboration opportunities for UK researchers. Researchers at UCL initially started the project but now includes staff at Diamond light Source and Imperial College London too. These UK researchers are now collaborating with staff at institutions in Germany and France on the project.[40] The Human Organ Atlas project has also enabled UK researchers to collaborate with international funders. These include the German Registry of COVID-19 Autopsies (supported by the German Federal Ministry of Health), as well as a $2.75 million donation from the US-based Chan-Zuckerberg Initiative.[41]

## Other impact areas

Arguably some of the research project's most notable impacts have been in terms of advancing healthcare treatments. As mentioned previously, the Human Organ Atlas project commenced in response to the COVID-19 pandemic. The work helped improve the understanding of how COVID-19 infection damages lungs, and also provided evidence on how COVID-19 leads to muscle disease in the heart. Consultees also spoke of how they expect the HiP-CT methodology developed through work at ESRF to help improve the understanding of Alzheimer's Disease (by being able to examine differences between white and grey matter in the brain), and of cancers.

[40] https://human-organ-atlas.esrf.eu/

[41] https://physicsworld.com/a/the-body-exposed/

Consultees also believed that there is a potential for spillover benefits to the healthcare system. There is hope that the methods used in HiP-CT could help inform the interpretation of MRI scans, and enable better 3D imaging of biopsy samples for instance. While there was an acknowledgment that very few places could provide the quality of equipment that ESRF does, there was a belief that a version of HiP-CT could potentially be used in national centres which had facilities similar to that of a synchrotron.

### The importance of the facility in achieving impacts

Representatives from the project's research group have spoken of the centrality of ESRF in enabling their work. While the project has also drawn on beamline time at other synchrotrons around the world including Diamond, the United States, and Japan. However, the ESRF's recent upgrade to the Extremely Brilliant Source (EBS) makes it the only fourth generation high energy source in the world. This upgrade means that ESRF now has the low-emittance, high-energy light source to penetrate an entire organ that is as thick as the heart, while resolving tiny changes in the density of soft tissue structures. By way of contrast, Diamond allows researchers to examine sample on a finger's thickness in detail, the human heart is 15-20 times thicker still, and therefore the high energy source provided through ESRF is required to study large intact human donor organs. Research group representatives were clear that some of their imaging would only have been possible through ESRF given the upgrade to EBS. While other synchrotrons such as The Advanced Photon source in Chicago have similar standard upgrades planned, these will not materialise for another 2-3 years meaning that ESRF was the only real solution available to them.

Consultees also spoke of the added value that ESRF provided in terms of the quality of its staff, and the quality of sample treatment facilities available too. By working with staff at ESRF, the research team have developed knowledge of how to pre-treat organs before experiments, something which they believe can help inform all future soft tissue radiography going forward.[42]

[42] Brunet, J., Walsh, C. L., Wagner, W. L., Bellier, A., Werlein, C., Marussi, S., ... & Tafforeau, P. (2022). Preparation of large biological samples for high-resolution, hierarchical, multi-modal imaging. Submitted to Nature Protocols. DOI: 10.1101/2022.07.02.498430

# Appendix B Safety of Lithium-ion Case Study

## Summary

Battery science, storage and engineering is a field with a myriad of real-world applications including consumer electronics, electronic vehicles (EVs), to storing renewable energy. Batteries must meet several criteria that batteries including, low costs, and durability, among others. Different sectors place different emphasis on each criterion in context to different application needs.

X-ray imaging diffraction and spectroscopy, techniques supported by ESRF, has enabled the research team[43], a collaboration between University College London, NASA and the ESRF, to understand how materials are assembled into devices and how devices are assembled into systems, in the context of different battery chemistries.

For this research project, the research team were specifically looking into improving the safety of lithium-ion batteries. When a battery fails, it fails rapidly, and has the potential to destroy itself.[44] The team studied two commercial batteries, with results showing the utility in tracking battery damage in 3D as well as in real time. At ESRF, the research team was able to test the maximum safety levels of batteries, exposing them to conditions well beyond the safe recommended operating window.[45] The objective of the research to increase the foundational knowledge in order for the design of safety features of batteries to be evaluated and improved.[46]

## Background

Traditionally, X-ray computed tomography (CT) had only been used to analyse battery failure mechanisms post-failure with static images, and to monitor changes to batteries under normal operating conditions. The team examined the batteries under more extreme conditions, exposing the battery shells to temperatures in excess of 250°C.[47] During this, they looked at the effects of gas pockets forming, venting and increasing temperatures on the layers inside two distinct commercial Li-ion batteries.

## The Research Project

With the objective of studying thermal runaway, a dangerous chain reaction in lithium-ion batteries that can lead to catastrophic fire[48], in batteries, the research team tested a type of rechargeable lithium-ion battery named "18650 cells". 18650 cells are commercially ready, with the potential to be used in electric vehicles and aerospace applications.[49] The team tested regular 18650 cells plus another kind that holds a unique feature: a polymer layer inserted into

[43] https://www.esrf.fr/home/Industry/industry-news/content-news/esrf-news-list/batteries-research-aims-to-design-safety-tests-for-lithium-ion-batteries.html

[44] ://www.esrf.fr/home/news/general/content-news/general/how-a-polymer-holds-the-key-to-safer-li-ion-batteries.html

[45] https://www.ucl.ac.uk/electrochemical-innovation-lab/research/imaging-diagnostics/battery-safety

[46] https://www.ucl.ac.uk/electrochemical-innovation-lab/research/imaging-diagnostics/battery-safety

[47] https://www.esrf.fr/home/news/general/content-news/general/li-battery-thermal-failure.html

[48] https://www.esrf.fr/home/news/general/content-news/general/how-a-polymer-holds-the-key-to-safer-li-ion-batteries.html

[49] https://www.esrf.fr/home/news/general/content-news/general/how-a-polymer-holds-the-key-to-safer-li-ion-batteries.html

the current collector.[50] The team combined high energy X-rays and thermal imaging to map changes to the internal structure and external temperatures of the two battery types while exposed to extreme heat.[51] The team required exceptionally high-speed imaging to capture the thermal runaway. This was achieved at the ESRF beamline ID15A, where 3D images can be captured in fractions of a second thanks to the very high photon flux and high-speed imaging detector.[52]

Using the ID15 beamline, and then the super-fast X-ray capabilities on ID19, the team combined X-rays with the information provided by a calorimeter, a tool that measures in detail the temperature profiles of a cell.[53] By combining the data of the beamline with the information from the calorimeter the research team gained a unique insight into how failure starts and can spread from one battery to another.[54]

## Impacts generated

*Scientific and research*

There have been many fundamental insights gathered from this research. The research team have found a solution to preventing thermal runaway. They now understand how the failure of a lithium-ion battery nucleates when it starts, as well as how it propagates. The team now has a greater understanding of what happens in batteries at a cell level, which is crucial to mitigating against battery failure. Moving forward the team now plan to study what happens with a larger sample size of batteries, particularly looking at what changes, at a microscopic level, cause widespread battery failure.[55] The research also demonstrates the application of ISC devices for intentionally inducing worst-case thermal runaway scenarios to test the efficacy of next generation cell or module designs in avoiding catastrophic failure.[56] In addition, the research has produced publications, has generated increased external collaborations for the research team, and has increased their potential for funding.

*Commercial and economic*

"Understanding how Li-ion batteries fail and potentially cause a dangerous chain reaction of events is important for improving their design to make them safer to use and transport". Hundreds of millions of rechargeable batteries are manufactured and transported each year as they are integral to modern living, powering mobile phones, laptops, cars and planes.[57] Despite the research focusing on the improvement of fundamental understanding, there is strong potential for the application of the research into industry. For example, with the

[50] https://www.esrf.fr/home/news/general/content-news/general/how-a-polymer-holds-the-key-to-safer-li-ion-batteries.html

[51] https://www.ucl.ac.uk/electrochemical-innovation-lab/research/imaging-diagnostics/battery-safety

[52] https://www.ucl.ac.uk/electrochemical-innovation-lab/research/imaging-diagnostics/battery-safety

[53] https://www.esrf.fr/home/Industry/industry-news/content-news/esrf-news-list/batteries-research-aims-to-design-safety-tests-for-lithium-ion-batteries.html

[54] https://www.esrf.fr/home/Industry/industry-news/content-news/esrf-news-list/batteries-research-aims-to-design-safety-tests-for-lithium-ion-batteries.html

[55] https://www.esrf.fr/home/news/general/content-news/general/li-battery-thermal-failure.html

[56] https://www.sciencedirect.com/science/article/pii/S0378775319300874

[57] https://www.ucl.ac.uk/electrochemical-innovation-lab/research/imaging-diagnostics/battery-safety

homologation process[58] for automotive batteries, there is a long and ever evolving certification and standards process. The research undertaken may help companies gain the evidence needed to successfully progress through certification. The research on the safety of lithium-ion batteries also provides insights for lithium-ion battery companies to strategize on how to mitigate against potential future failures and challenges.

### The importance of the facility in achieving impacts

According to research team representatives, ESRF provides the highest X-ray source of all the worlds synchrotrons. In terms of fundamental characteristics of the accelerator, "the ESRF is almost without peer in terms of the actual capability for the synchrotron radiation it generates". It enables the research team to work faster, exercise new techniques, and conduct more experiments. The team would not have been able to carry out their research, at least not in the same way, or in the same timeframe, without the facility.

ESRF has also provided opportunities for the research team to further develop their skills in terms of health and safety, both around the operation of the experiments and in terms of radiation physics as well. Additionally, ESRF has enabled the team to grow their professional network, benefiting enormously from the exposure to international colleagues at the facility.

[58] Homologation is the type of approval procedure in motorsports that requires a vehicle, a racing track, or a standardized item to be certified to race in a specific league or series. In simple words, the process of testing and certification for adherence to technical standards is known as type approval. The series' sanctioning organization sets the norms and rules that must be followed. Homologation is the procedure by which the official authority approves the vehicle once it passes the organization's tight requirements.: https://e-vehicleinfo.com/ev-homologation-cost-process-requirements-and-testing/

# Appendix C XMaS Scientist Experience Case Study

## Summary

XMaS is an EPSRC funded National Research Facility located at the ESRF which supports the broad UK materials science communities. It provides free at the point of access to synchrotron radiation at the ESRF.[59] Since 2015, XMaS has successfully applied a growing outreach programme aimed at tackling gender bias in Physics. They run an annual national competition, resulting in a group (typically numbering sixteen) of 16-18 year old female students taking a trip to visit the European Photon and Neutron campus in Grenoble, and touring both the ESRF and the XMaS beamline. Participants conduct mini research projects, give a presentation, tour the campus, and meet female scientists working at the facility.

## Background

The initiative's origins came from the XMaS team discussing ways of encouraging and enthusing more young women into science, particularly physics. The team realised there was a need to inspire young women into careers in science, and to show them that success in a science career for women is possible. They developed a programme centred on practical experiments at the ESRF, but with the primary aim of introducing the young students to older female role models and the work they do. The idea is to allow the young students to talk freely to female scientists about their work, their research, and their careers; letting them ask any questions they may have in an informal manner. Ultimately, the programme looks to inspire and enthuse the next generation of scientists.

Originally the initiative focused on students from around Warwick and Liverpool but has now expanded to include the whole of the UK. To win a place on the trip, the students are challenged to conduct research on a famous female scientist. During their time at the facility, they are asked to conduct a mini research project and then prepare a presentation which they present to their peers. They are taken around the beamlines at the ESRF and explore the facility more widely. They are then invited to eat lunch and socialise with the scientists at the facility as well as take up the opportunity to explore the city of Grenoble.

*Skills benefits*

According to programme representatives, the main skills benefit for the participants, is being surrounded by other like-minded science enthusiasts, which has helped to build up confidence in their love of science. The initiative also gives the young students a positive image of a career in science, being something within reach and to aspire to. The students have a WhatsApp group where they chat to each other, and stay connected even after the initiative.

## The importance of the facility in achieving impacts

According to the programme staff, as a result of the trip, the student's perceptions and stereotypes of people working in STEM careers is challenged and changed. They see the collaborative nature of working in the sciences first hand, in contrast to the perception many of the students held that life as a scientist was a somewhat isolated experience. The opportunity

[59] https://www.xmas.ac.uk

also provided an inspirational setting to see science 'beyond the classroom', but with direct relevance to the school curriculum and international research in the 'real world'.[60]"

Additionally, they see how big research infrastructures like the ESRF provide a space for international collaboration, co-working and interdisciplinarity, which the XMaS team is keen to showcase to the young female students. In interviews, leaders stated that the ESRF provides a unique opportunity to showcase the benefits of international partnerships.

[60] https://www.materialstoday.com/materials-chemistry/articles/s1369702115002205/

# Appendix D Work by UK Catalysis Hub Case Study

## Summary

The UK Catalysis Hub focuses on achieving breakthrough in catalytic sciences. One of the research teams at the Hub have used ESRF infrastructure, high energy X-rays above 40 keV, to study catalysis and heterogenous catalysis[61] under operando (real working) conditions. In addition to novel scientific results, including approaches to analysis, the results have applications in the areas of emission control and energy storage – both of which are seeing industrial and scientific interest from outside the Hub.

## Background

The UK Catalysis Hub was launched using funding from EPSRC and situated at the Research Complex at Harwell. The initial £12.9 million in 2013[62] was followed by further £14 million in 2018[63]. The goal for the Hub is to become a leading research centre for catalytic science and promote new breakthroughs in catalytic science.[64] The Hub's work with the ESRF infrastructure started from the need to access high energy X-ray beams, something which ESRF was able to provide.

## The Research Project

According to one of the Principal Investigators (PIs) at the UK Catalysis Hub, the research at ESRF involved analysis of material performance in operando conditions, specifically in the area of catalyst and heterogeneous catalysts. In undertaking this analysis, members of the UK Catalysis Hub have used X-ray imaging techniques to pioneer new developments in synchrotron-based X-ray diffraction computed tomography imaging at ESRF.[65]

The breakthrough (detailed further below in the discussion of impacts) were made possible by the availability of ESRF X-ray facilities, with the PI particularly noting the availability of high energy, "hard" X-ray beams above 40 keV. This allowed the team to develop their novel technique of synchrotron-based X-ray diffraction to study catalysts. The approach has been developed to: "yield 2D cross-sectional information in multimodal mode (i.e. simultaneous acquisition of absorption, fluorescence and diffraction contrast information) as well as in rapid acquisition mode (20 ms per dataset) for a more complete characterisation of functional materials".[66] This level of material characterisation is based on 5D imaging which is achieved by introducing chemical imaging and allowing for more nuanced interpretation of data.[67]

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[61] Heterogenous catalysis is a catalysis where the phase of the catalysts differs from the reactant and typically involves solid phase catalysts and gas phase reactants.

[62] University of Bath (2013). Bath to receive funds from £12.9 million investment. Available at: https://www.bath.ac.uk/announcements/bath-to-receive-funds-from-12-9-million-investment/

[63] RCaH (2018). EPSRC announces further £14 million to keep UK Catalysis Hub sparking. Available at: https://www.rc-harwell.ac.uk/epsrc-announces-further-14-million-to-keep-uk-catalysis-hub-sparking/

[64] UK Catalysis Hub (2022). About Us. Available at: https://ukcatalysishub.co.uk/about-us/

[65] ESRF (2014). Illuminating the physical process of catalyst deactivation. Available at: https://www.esrf.fr/home/UsersAndScience/Publications/Highlights/highlights-2014/SOM/SOM13.html

[66] UK Catalysis Hub (2022). Exploitation of Facilities. Available at: https://ukcatalysishub.co.uk/exploitation-of-facilities/

[67] Chemical imaging producing a spectrum of colour within the image results rather than contrasts

## Impacts generated

*Scientific and research*

The Hub's usage of ESRF has continuously evolved over the past decade with improvements to the facility also contributing towards new breakthroughs. Through ESRF usage, the Hub developed novel synchrotron-based X-ray diffraction computed tomography imaging, a major impact in its own right. In turn, the new technique has enabled scientific impacts including:

- "Observation of subtle differences in Co nanoparticle structure and the correlation with selectivity during Fischer-Tropsch Synthesis at elevated pressures"
- "Observation of the active PtMo state during liquid phase hydrogenation of nitrobenzene and the successful demonstration of 5D imaging to reveal gradients in the type and nature of the active phase during partial oxidation of methane at 700 °C.[1-3]"

According to the PI, these breakthroughs were novel for their time, and continued to generate interest from other researchers/research groups for collaborations, as well as from industry about potential application of the approaches and technologies. The (itself a major impact) allowed for the following scientific impacts include:

The PI at the UK Catalysis Hub considers that further breakthroughs are possible as ESRF continues to upgrade their facilities. Specifically, there is a belief that upgraded ESRF infrastructure will enable catalyst scientists to study "sub-micron resolution, sub-second 2D data collection (yielding 5D data in ~ minutes) and the possibility to further develop imaging capabilities using photon-in/photon-out spectroscopies or total scattering".[68] Furthermore, the PI considers that software developments within ESRF could lead to real-time multi-dimensional imaging – something that is still regarded as a difficult prospect but one that could ultimately make older imaging techniques obsolete.

*Commercial and economic*

The developments surrounding catalysts are applicable in areas related to carbon emission control, particularly within the automotive industry. As catalysts are used by car manufacturers to achieve greater efficiency in reducing harmful emissions, the work at the UK Catalysis Hub has the potential to positively impact the automotive industry, using the fundamental research results and publications from ESRF-based work to develop improved solutions.

*Skills benefits*

According to a PI based at the Hub, the Hub's post-doctoral researchers have particularly benefited from work based at ESRF. Placements typically last up to a year and have given post-doctoral researchers the chance to encounter real challenges in the field which are considered to be important learning experiences for early career researchers. There have also been wider benefits in terms of the ability to adopt interdisciplinary approaches too.

*UK's international standing*

The results emerging from their research have contributed to catalytic sciences, introducing new techniques and concepts for catalysis sciences (i.e., synchrotron-based X-ray diffraction computed tomography imaging, multimodal mode) that have been recognised

[68] UK Catalysis Hub (2022). Exploitation of Facilities. Available at: https://ukcatalysishub.co.uk/exploitation-of-facilities/

internationally. The research team at UK Catalysis Hub continues to see growing demand for their approaches not only from researchers but other facilities (specifically Deutsches Elektronen-Synchrotron DESY). In other words, international research organisations are now interested in the use of know-how generated at UK Catalysis Hub (via their work at ESRF) to help upgrade their equipment and methodologies, and in turn, help achieve greater scientific outputs.

*Other impact areas*

According to one of the Hub's PIs, a more recent impact pathway is in the field of energy. Research findings emerging from ESRF usage have allowed a study of "functional materials used as catalysts and in energy storage with novel chemical imaging techniques using X-ray scattering and/or spectroscopic methods".[69] The team from UK Catalysis Hub is now working with the Faraday Institution (a UK research institute examining electrochemical energy storage) in examining potential improvements to energy storage and cleaner energy.

## The importance of the facility in achieving impacts

ESRF has offered the team at the UK Catalysis Hub access to high energy X-ray beams that led to scientific breakthroughs in catalyst science. The research infrastructure available at ESRF is regarded as unparallel in the balance between high-end, high-energy equipment and accessibility. ESRF is also noted for its international dimension –enabling easier cross-border collaborations with member country researchers. Furthermore, it gives more international visibility to research projects. To that end, members of the Hub are clear that the facility has been central to the development of catalyst science in the UK.

[69] UK Catalyst Hub (2020). Past Webinar: Prof. Andrew Beale (Professor of Inorganic Chemistry, Dept of Chemistry UCL/ Finden Ltd). Available at: https://ukcatalysishub.co.uk/webinar-prof-andrew-beale-professor-of-inorganic-chemistry-dept-of-chemistry-ucl-finden-ltd/

technopolis group

www.technopolis-group.com