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Socio-economic impact evaluation study of the UK subscription to ESO

Final Report – Summary

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Executive Summary

The UK's **Science and Technology Facilities Council (STFC)**, part of UK Research and Innovation (UKRI), operates a range of world-class research facilities in the UK and manages UK access to several others internationally. These are essential to the delivery of the Council's three-part vision (discovering the secrets of the universe, developing advanced technologies and solving real-world challenges), while also supporting UKRI's mission of convening, catalysing and investing to build a thriving R&I system for the UK.

One such international facility is **the European Southern Observatory (ESO)**, which designs and operates some of the largest telescopes in the world, providing state-of-the-art facilities for astronomers and astrophysicists in its Member countries (including the UK, which joined in 2002).

STFC commissioned Technopolis to undertake an **evaluation of the UK subscription to ESO,** encompassing an impact evaluation of the benefits of membership, a process evaluation focusing on industrial return, and the development of a framework for future monitoring efforts.

Main Findings from the Impact Evaluation

World-Class Research

- **ESO supports state-of-the-art research**, using some of the most advanced technologies and sophisticated techniques available. It has made critical contributions to advancing understanding of the Universe, e.g. in showing its expansion is accelerating (2011 Nobel Prize), providing evidence of the black hole in the centre of our own galaxy (2020 Nobel Prize) and enabling the search for other Earth-like planets outside our solar system.
- **UK scientists have preferential access to ESO facilities and are very active users**, accounting for 15-20% of proposals for observation time each year. The UK also has above average success rates, and was awarded 29% of time in 2019/20 (while contributing 17% of fees).
- **ESO is the most productive astronomical observatory**, with over 17,000 publications based on ESO data and more than 1,000 more added each year. Nearly half of new ESO papers now involve a UK author, up from just 13% in the period before the UK joined. ESO's science archive contains 1.5m images and 1,640TB of data, which is used heavily to support further research, especially by large numbers of UK PhD students and post-docs.
- It is difficult to maintain a very high impact as production volume goes up. As such, the UK's combination of high output and high (and improving) citation profiles in the astronomy and astrophysics subfield since the UK joined ESO is a **very strong achievement**.

World-Class Innovation

- **UK scientists and engineers in research laboratories and universities have been heavily involved in ESO instrument development**, receiving guaranteed observation time in exchange. The UK's significant involvement also makes it well placed to take advantage of instruments once installed. The number, scale and duration of ESO projects involving STFC's UK Astronomy Technology Centre (UK ATC) and Rutherford Appleton Laboratories in particular has provided these institutes with a valuable platform for capability development and increased reputation.
- **ESO has supported the development of novel technologies**, including sodium lasers, cryogenic bearings and time reference systems, much of this with UK involvement. New applications underpinned by these technologies deliver wider societal impact, including cancer detection and treatment, as well as satellite communications.
- **Membership gives UK companies preferential access to ESO contract opportunities**, supporting innovation across a wide spectrum of UK industry.
- **At least 258 different UK organisations have been involved in successful bids to ESO**, with contracts relating to insurance, optical imaging detectors, large optics, filters, software, civil engineering, cryogenics and consultancy, amongst others.
- **The UK secured £117m in ESO contracts between 2002 and 2020** (an average of £6.1m per year), which is 12% of the total going to all Member States during this time. In some years it has done even better, securing close to a quarter of the total value of contracts awarded.
- **In addition to the direct value of these contracts, UK suppliers report wider benefits**, including new knowledge and capabilities, staff satisfaction and access to new contacts. ESO contracts also bestow credibility and prestige on the businesses concerned. Around 40% of UK suppliers reported seeing an increase in sales income elsewhere as a result.

World-Class Skills

- **ESO offers a wide range of training and skills development opportunities**, such as fellowship and studentship programmes, that are predominantly available to ESO Member States. There have been ~80 UK fellows and students since joining, equating to ~14% of the total in recent years.
- **Most UK users reported that ESO had had a significant or critical impact** on their ability to work in an international environment and on their experimental skills, as well as their team working, project management, communication, computing and problem-solving skills.
- **Those with ESO experience are highly sought-after in the UK economy**, both in- and outside of astronomy and academia, e.g. taking programming and data mining skills into areas as diverse as finance, remote sensing, human behaviour analysis and meteorology. Most respondents from the UK user community (78%) also claimed that the UK's involvement in ESO was significant or critical for attracting top scientific and engineering talent to the UK.
- **ESO, its Members and the media communicate activities and discoveries to the UK public**, raising the profile of astronomy and increasing interest in science and technology.

Science diplomacy

- **ESO is very visible internationally** and acknowledged as a leading centre of scientific research. The UK's membership provides it with wider opportunities and benefits, including:
  - A platform for international engagement, leadership and agenda-setting.
  - An ability to influence decision making, enhancing alignment with UK capabilities and priorities.
  - More favourable perceptions of the UK as a country to partner with or invest in.

Costs and (monetised) Benefits

The pooled investments of ESO Members have enabled instruments and facilities that could not be developed by any one member alone. The UK's 17% contribution supports the construction, maintenance and operation of the observatories, plus 700 staff, and provides the UK with preferential access to the facility. **UK contributions** have averaged £22.7m per year (2020 prices) over its 19 years of membership (excluding joining fees and a special contribution for the Extremely Large Telescope).

The small proportion of **socio-economic impacts suitable for monetisation**, resulted in a conservative estimate of £45.5m per annum in benefits for the UK (2020 prices), complemented by a wide range of non-monetised impacts across research, innovation, skills and diplomacy.

Recommendations for future monitoring

An updated monitoring and evaluation framework has been proposed for STFC to use in tracking the benefits flowing from the UK's subscription to ESO. This would ensure a more wide-ranging and robust assessment of achievements and an enhanced evidence base.

Main Findings from the Process Evaluation

STFC plays a key role in promoting opportunities for UK companies to win commercial contracts from international facilities, ensuring a return from public investments.

Increasing the UK's industrial return from ESO is a long-term goal, that is sensitive to ESO spending cycles and requires long-term commitment and investment. The UK's return has been weaker in the last few years, largely due to it not leading the physical construction of the ELT.

Returning the UK's return coefficient (the ratio between its share of contract value and its share of membership contributions) to the 'good' levels achieved historically is a key challenge.

Recommendations for increasing the UK's industrial return from ESO

The evaluation has put forward a series of recommendations for the UK ESO Industrial Liaison Officer (ILO) and wider STFC Business Opportunities team that may help to improve the UK's industrial return from ESO in future. This includes suggestions for additional help to suppliers in understanding and interpreting requirements or in meeting the costs of bidding, further development of internal management tools and databases to better track industry engagement and target future support efforts, and looking for additional opportunities to leverage the capabilities, resources and activities of partners to raise awareness and support new and existing UK suppliers to benefit from the opportunities available through ESO.

1 Introduction

1.1 The European Southern Observatory

The **Science and Technology Facilities Council (STFC)**, part of UK Research and Innovation (UKRI), is keeping the UK at the forefront of international science and tackling some of the most significant challenges facing society such as meeting our future energy needs, monitoring and understanding climate change, and global security. STFC operates a range of world-class research facilities in the UK and also manages UK access to several others internationally. These are essential to the delivery of the Council's three-part vision of discovering the secrets of the universe, developing advanced technologies and solving real-world challenges, while also supporting UKRI's mission of convening, catalysing and investing to build a thriving R&I system in the UK.

One such international facility is **the European Southern Observatory (ESO)**, of which the UK has been a member since 2002. ESO is currently the foremost intergovernmental astronomy organisation. It designs and operates some of the largest telescopes in the world, providing state-of-the-art facilities for astronomers and astrophysicists within its Member countries.

1.2 The Evaluation Study

STFC commissioned Technopolis to undertake a **socio-economic impact evaluation study of the UK subscription to ESO**. There were three main elements to this work:

- An impact evaluation of the benefits to the UK from its membership of ESO since 2002
- A process evaluation, focused on exploring the UK's industrial return from ESO
- A future evaluation framework and plan for monitoring benefits of ESO membership

The study itself was undertaken in phases between March 2020 and mid-2021 and involved **multiple strands of data collection**, plus the analysis of existing evidence. This included:

- Desk research and analysis of existing data and information collected by STFC and ESO
- Surveys of the UK user community (133 responses) and UK suppliers (78 responses)
- Interviews with 48 stakeholders from across STFC, ESO, UK users and suppliers
- A bibliometric analysis of all ESO publications 1996-2019
- The development of a series of vignettes and case studies to exemplify specific benefits

Following an initial scoping stage, the main phase of evaluation began in August 2020 and continued until September 2021 with the delivery of this report for publication.

1.3 This Summary Report

This document is the **Summary Report for the evaluation** and sets out the key findings and conclusions from the study. It has three main sections:

- A brief introduction to ESO, its facilities and activities
- Key findings from the impact evaluation, including benefits relating to research, innovation, skills and science diplomacy, plus a comparison between the costs and (monetised) benefits of the UK's investment in ESO, and recommendations for future monitoring
- Key findings from the process evaluation, including an assessment of UK achievements (return) to date and an exploration of the challenges and barriers faced in bidding successfully for ESO contracts, plus recommendations for increasing UK return in future.

An accompanying Evidence Document provides further information on the findings, as well as additional background and methodological detail.

2 A brief introduction to ESO, its facilities and activities

Five founding nations signed the ESO Convention in 1963 and chose Chile as the site for the first observatory. Now, almost 60 years later, ESO is currently the foremost intergovernmental astronomy organisation in Europe and the world's most productive astronomical observatory. It designs and operates some of the largest telescopes, providing state-of-the-art facilities for use by astronomers and astrophysicists, predominantly within its Member countries and Chile.

ESO now has **16 Member States**, along with the host state of Chile and Australia as a strategic partner. The UK became the 10th member when it joined in 2002. This membership provides the UK with access to ESO facilities and observatories, plus opportunities for UK companies to bid for industrial contracts to develop new technologies and provide products and services. Membership also provides preferential access to the Atacama Large Millimeter/submillimeter Array (ALMA) – a separate facility delivered by a partnership of the USA, Canada, Taiwan, South Korea and Japan, in cooperation with Chile. In addition, scientists and engineers from Member States can form consortia to develop scientific instruments for ESO, usually receiving guaranteed observation time in exchange. ESO also offers a range of training and skills development opportunities, plus outreach and public engagement activities and materials.

ESO's budget — used for the construction, maintenance and operation of observatories, plus 700 staff — is made up almost entirely of subscription fees from Member States. Annual contributions total £165m (2020 figure), with each country contributing in proportion to their national income. The UK (via STFC) is currently the second largest contributor, after Germany, paying 17% of fees in 2020 (~£28m), which includes an element for the construction of the Extremely Large Telescope (ELT). The UK contribution equates to 4% of STFC's total budget.

Over its 19 years of membership (2002-20), UK contributions to ESO have totalled £432m, or £22.7m per year on average (2020 prices).

In addition there have been other one-off costs over time (an accession fee and an additional contribution for the ELT construction programme), worth £226m (in cash and in-kind).

STFC is also currently funding ~£6.5m per year from its core budget to UK institutes for ESO Instrumentation research and development programmes.

Composition showing all the ESO observatories and the Headquarters

Credit: ESO/M. Kornmesser

ESO **observatories and telescopes** are located in Chile, where it operates three observing sites. Some of the instruments at these sites are developed 'in house', but the majority are developed with international consortia of research organisations, with ESO defining and contributing to the design and implementation at the observatories. In parallel, ESO runs procurement processes for products and services, where the key principles are to procure from Member States, whilst seeking fair distribution of contracts amongst them.

Each country may appoint an Industrial Liaison Officer (ILO) to establish contact between ESO and potential suppliers. STFC's ILOs (for ESO and other facilities) are responsible for contributing to a database of potential suppliers (for all STFC large facilities), running engagement events and communicating contract opportunities.

The process to allocate **time on telescopes** (other than ALMA) is run by ESO, and is decided on the basis of scientific excellence and a ranking of proposals. Proposals are invited twice a year from any institution, including (with limitations) from outside of Member States. In addition, those involved in ESO instrument development are awarded guaranteed observational time, while 10% of the observing time is reserved for Chilean astronomers (typically in collaboration with astronomers from ESO Members). Observing time on ALMA is allocated through a separate, annual process based on scientific merit within the proportion available to the ESO community.

The ESO **Science Archive** Facility then contains data (over 1.5 million images or spectra) from ESO's various observation programmes. ESO also operates the European copy of the ALMA Science Archive. Other supporting facilities include the headquarters, the ESO Supernova Planetarium and Visitor Centre (all in Germany), and the European ALMA Regional Centre.

ESO's online curated **bibliography** (telbib) provides a database of refereed papers published by the ESO user community, with links to data in the ESO Science Archive. All of the ~17,000 articles and papers (published 1996-2020) use data from ESO facilities (in part or entirely).

ESO employs some 700 people and runs Fellowship and Studentship programmes each year. It also undertakes public engagement activities, mainly run through its sites in Chile and the Supernova Planetarium and Visitor Centre in Germany. It also contributes to conferences, exhibitions, and workshops across member states. ESO has a strong internet presence over a variety of platforms and also provides extensive material for use by the public and educational institutions.

3 Key findings from the impact evaluation

3.1 Introduction

ESO's strands of activity and engagement are multi-faceted (fundamental research, industry contracts, student placements, public engagement activities) and benefits to the UK may flow both directly (e.g. via UK contractors, training attendees or users) and indirectly (e.g. through the uptake of published knowledge or the adoption of technologies developed at or for ESO). There are therefore a wide range of types of benefits and impact, flowing through a series of interrelated impact pathways, for the study to explain, explore, capture and measure.

To structure this complexity, the study developed a framework that identifies **12 main areas of potential benefit to the UK** from its investment / involvement in ESO, organised under STFC's strategic goals of world-class research, innovation and skills (see below). A final set of benefits relating to science diplomacy is also included, given the international collaborative nature of ESO. These areas of benefit are used to structure the impact evaluation findings.

Table 1 Impact areas and pathways for the UK's benefits from its subscription to ESO

Objective	Areas of benefit to the UK
1. World-class research	1.1 Pushing the frontiers of human knowledge & understanding, enabling further scientific progress 1.2 Sustaining the UK's research excellence & leadership through access and opportunities at ESO 1.3 Attracting investment & talent through improved perceptions of the UK
2. World-class innovation	2.1 UK benefits from the wider application of ESO-derived technologies 2.2 UK benefits from the wider application of ESO-supported research 2.3 Increased performance amongst UK suppliers to ESO / ESO projects
3. World-class skills	3.1 Increased skills and capabilities of the UK workforce 3.2 Increased UK public understanding of - and support for - science 3.3 Increased (future) UK STEM workforce
4. Science Diplomacy	4.1 UK benefits from stronger influence in the international science and technology landscape 4.2 UK benefits from improved diplomatic relations 4.3 UK benefits from enhancements to its image as a 'great science & innovation nation'

In exploring the benefits to the UK from its membership of ESO, **it is important to consider the counterfactual**, which refers to the hypothetical situation where the UK is not a member of ESO. The comparison — between the benefits realised as a member, and the likely benefits without membership — represents the true *additional* value of the UK's investment in ESO. As already introduced, membership provides the UK with access and opportunities relating to ESO that would not be available (at least to the same degree) if it were not a member and investing in the facility. However, the difference (membership to non-membership) is not always clear-cut, and the gains obtained from the membership are often a matter of intensity or scale, rather than benefit / no-benefit. This counterfactual is therefore explored and discussed at various points in the findings, in relation to different aspects of the UK's interactions with ESO.

In addition, not all benefits to the UK from ESO are direct or exclusive. The UK can benefit, for example, from the knowledge and understanding developed through ESO, via access to publications, data and images produced by others. It can also benefit from the advances in technology made at ESO, which can then be deployed in other similar facilities, or in completely different areas of the economy. These kinds of benefits could flow to the UK anyway, even without membership. However, it is reasonable to assume that the UK's 'closeness' to the facility via its membership makes this more likely. Also, the scale of these benefits (and some of the specific advances made) would not be possible without the UK's involvement as a member. Its contribution to this pooled endeavour (currently ~17% of member contributions) makes a substantial difference to the scale, speed and ambition of ESO's development and activities and therefore to the global benefits that are available as a result.

A more detailed discussion of the counterfactual can be found in Section 10 of the accompanying Evidence Document.

Finally, Government guidelines advise **giving a monetary value to impacts wherever possible**, while other (non-monetisable) benefits should be recorded (and quantified in another way, to give a sense of their magnitude). Monetising the impact from Research Infrastructures is a challenge, however, for all evaluators and funding bodies, and not all identifiable benefits to the UK from its investment and involvement in ESO are monetisable. Where there was sufficient data and a robust approach available, we have attempted to capture and assign a value, arriving at a total of £45.5m per year in monetised benefits for the UK (2020 prices) (see Section 3.6 for further details). This figure is a minimum, however, and does not capture the full range of impacts emerging from ESO, which are explored (but not monetised) in the next sections.

3.2 Benefits relating to world-class research

ESO supports state-of-the-art research in astronomy, using some of the most advanced technologies and sophisticated techniques available. These facilities were regularly highlighted by those consulted for the study as being the "best in the world", perfectly situated in an area (high, dry and unpolluted) that has the clearest night skies (and most frequently), and "leagues above" anything else available in the southern hemisphere. It has made critical contributions to advancing our understanding of the Universe, enabling important discoveries, and supporting further research.

Major discoveries enabled by ESO include:

- Showing that the expansion of the Universe is accelerating (2011 Nobel Prize)
- Capturing the first image of a supermassive black hole
- Obtaining the first image of a planet outside our solar system (173 light years away)
- Revealing effects on the motion of a star passing through the extreme gravitational field near a supermassive black hole
- Evidence of the black hole in the centre of the Milky way (2020 Nobel Prize for the UK)

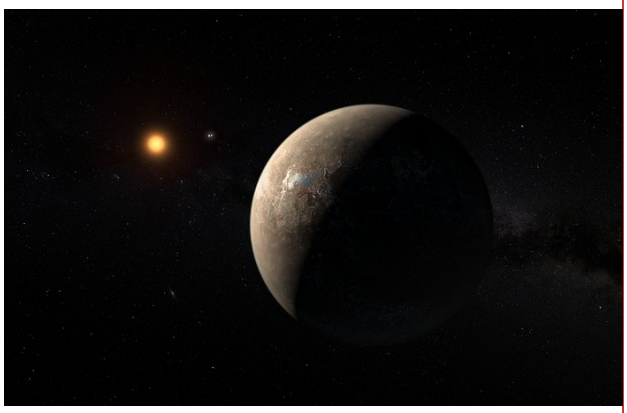
Box 1 Discovery of exoplanets

Didier Queloz (Professor of Physics at the Cavendish Laboratory, University of Cambridge) was at the origin of the exoplanet revolution in astrophysics, discovering the first giant planet outside the solar system (*51 Pegasi b*) in 1995. This seminal discovery (for which he was awarded the 2019 Nobel Prize) spawned a revolution in astronomy, both in terms of new instrumentation and understanding of planet formation and evolution. Professor Queloz has been a long-standing collaborator with ESO and over the subsequent 25 years has continued to make progress in detection and measurement capabilities of exoplanet systems. He was quoted in the recent ESO impact study[1], saying "ESO was the key to the success of my career and gave me the opportunity to be involved in building cutting-edge instrumentation and access to a wide community. In the end, 90% of my papers are related to ESO."

51 Pegasi b was first detected using the ELODIE spectrograph in France and the success of this instrument led to the construction of CORALIE at ESO's La Silla Observatory in Chile. The knowledge gained from the building and operating of both these instruments was then put into the development of the High Accuracy Radial velocity Planet Searcher (HARPS), which began operations in 2003.

Attached to the ESO 3.6-metre telescope, HARPS searches nightly, and with unparalleled accuracy, for exoplanets, and is one of the most successful planet finders in the history of astronomy. For example, in 2011 the team behind HARPS reported the discovery of 50 exoplanets, including 16 new super-Earths (masses 1-10 times that of the Earth). HARPS, at that time, was responsible for two thirds of all the known exoplanets with masses less than that of Neptune and, thanks to its observations, astronomers have calculated that there are billions of other rocky planets in the habitable zones around red dwarfs in the Milky Way, including about one hundred in the Sun's immediate neighbourhood.

In 2016 HARPS was used to find the first planet around the closest star to earth (other than the Sun). A team of astronomers led by Guillem Anglada-Escudé (Queen Mary University of London) used ESO telescopes to find clear evidence of a planet orbiting Proxima Centauri. The planet (*Proxima b*) orbits its cool red parent star every 11 days and has a temperature suitable for liquid water to exist on its surface. This rocky world is a little more massive than the Earth and is the closest exoplanet to us — and it may also be the closest possible abode for life outside the Solar System.



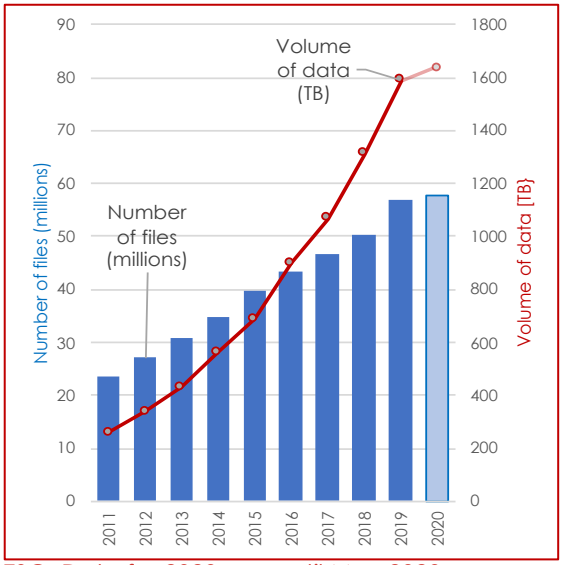
Artist's impression of planet orbiting Proxima Centauri. Credit: ESO/M. Kornmesser.

ESO is the most productive astronomical observatory in the world, with research producing large volumes of data that can be analysed to test hypotheses and produce new insights, typically resulting in peer-reviewed publications. Its Science Archive (data resulting from ESO's various observation programmes) has grown steadily to 58m files, 1.5m images and 1,640TB of data in 2020 (Figure 1). This is essential for the continued development of survey-based observations, and likely contains large amounts of useful information for as yet unstudied astrophysical phenomena (a quarter of UK publications relating to ESO each year make use of the archive). In this way, the legacy of ESO-enabled observations continues to grow over time.

Similar growth has been seen in ESO's online curated bibliography of papers using ESO data (telbib), which now contains 17,000 publications, with more than 1,000 new papers now added each year (Figure 2). Most (99%) of these papers are in the astronomy and astrophysics subfield, where in recent years ESO has accounted for nearly 10% of the total global output.

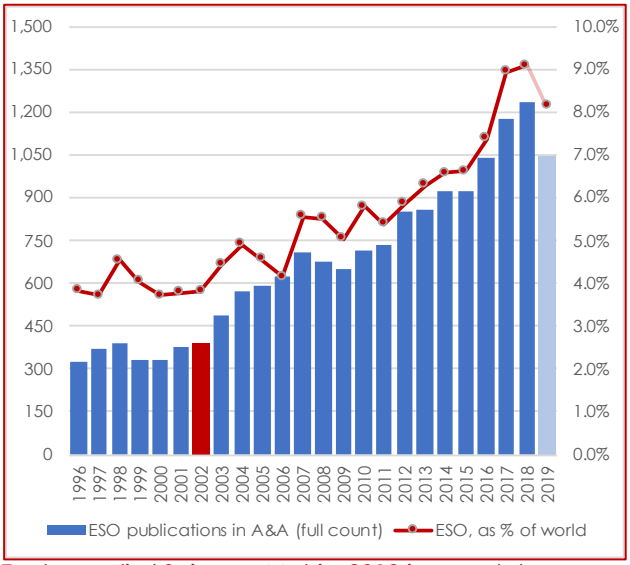
[1] ESO's Benefits to Society, January 2021

Figure 1 ESO Science Archive holdings



ESO. Data for 2020 runs until May 2020.

Figure 2 ESO publications, astronomy & astrophysics



Technopolis / Science-Metrix. 2019 incomplete.

The data and papers produced through ESO are available for UK scientists to build on, supporting further scientific progress, in astronomy and beyond. The UK is one of the most active users of the archive, with over 911 users registered between 2012 and 2020 (11% of the total), who accounted for a quarter of all files and data downloaded. Interviewees highlighted that access to this data is particularly essential to the next generation of UK astronomers, with large numbers of PhD students and post-docs using the archive as the backbone for their research.

> *"Of the 6 funded UK postdocs I have supervised, 4 were based on ESO observations. Of my 16 UK PhD students, 11 were based on ESO data and 3 were based on ESO funding."*
>
> *(Respondent to survey of UK users)*

Access to this archive is open to all (regardless of membership status). However, ESO Principal Investigators (PIs) — the majority of whom are from member countries, due to the rules around access to observation time — have exclusive access to their observation data for a year before it is made more widely available. Whilst use of the archive is growing, the majority of ESO publications (89% in 2019) are still based on PI data only (or PI data combined with archive data), demonstrating the important role of this exclusive access for the UK and other Members.

Bibliometric analysis similarly shows significant and widespread use of ESO-enabled knowledge in the UK. More than 2,000 UK scientific papers now cite ESO articles each year (on average, 2014-19). This includes most (~70%) of the UK papers that are published in the astronomy and astrophysics subfield. In the period before the UK joined ESO, this figure was much lower (just 268 UK papers per year citing ESO publications).

The vast majority (88%) of **UK papers citing ESO publications** (1996-2019) are in the astronomy & astrophysics subfield. However, citations also appear in papers across all 48 other sub-fields used in the analysis (including those shown below), demonstrating the breadth of ESO's relevance across scientific fields.

- Nuclear & Particle Physics (2,146 UK papers)
- General Physics (505)
- Optoelectronics & Photonics (280)
- Chemical Physics (93)
- Fluids & Plasmas (82)
- Meteorology & Atmospheric Sciences (75)
- Aerospace & Aeronautics (74)
- Geochemistry & Geophysics (53)

The UK papers citing ESO publications also include some of the most influential; 17% of the UK papers citing ESO research are among the 10% most cited globally (i.e. well above average).

Citations are a good proxy for contributions to subsequent knowledge generation and — across all metrics tested by the study — ESO's publications perform well above average. For instance, in the most recent six-year period, the proportion of ESO papers falling within the 1, 5 and 10% most highly-cited in their field globally has been 60-90% above average.

Pooled investment in ESO (both resources and expertise) has enabled instruments, facilities and infrastructure to be built that could not be developed by any one member alone. The increasing cost and complexity of successive generations of facilities and instruments has placed such investments beyond the reach of all but the largest countries. To take one example, ESO's Extremely Large Telescope (ELT) — a revolutionary telescope currently under construction — will alone cost €1.2bn to construct (nearly double STFC's annual budget) and tens of millions of Euros a year to operate. Membership therefore provides the UK with preferential access to facilities that cannot be replicated domestically. The UK now pays 17% of the annual cost of the facility, down from 20-21% when it joined. Its annual subscription fee (£24m in 2020) contrasts with the current (depreciated) asset value of ESO, which totals in excess of £1.1bn (2019).

In return for investment, UK scientists have preferential access to ESO facilities (plus others, such as ALMA and the Cherenkov Telescope Array [under construction]), as well as participation in research underpinning ESO's technology projects. This includes access to technology and capabilities that are not otherwise available, international collaboration networks and knowledge sharing, the latest developments in science and technology, and new methods and techniques.

Interviewees highlighted the value of the scale, breadth and variety of telescopes and instrumentation co-located at ESO, which increases the likelihood that required resources are available and that a much wider community of researchers are provided for. The broad portfolio of telescopes and instruments also offers astronomers with a unique toolbox with which to explore the cosmos over a wide range of wave-lengths. Many of the instruments are considered to be best-in-type worldwide, while some have completely unique capabilities, meaning that the data obtained can often not be achieved elsewhere.

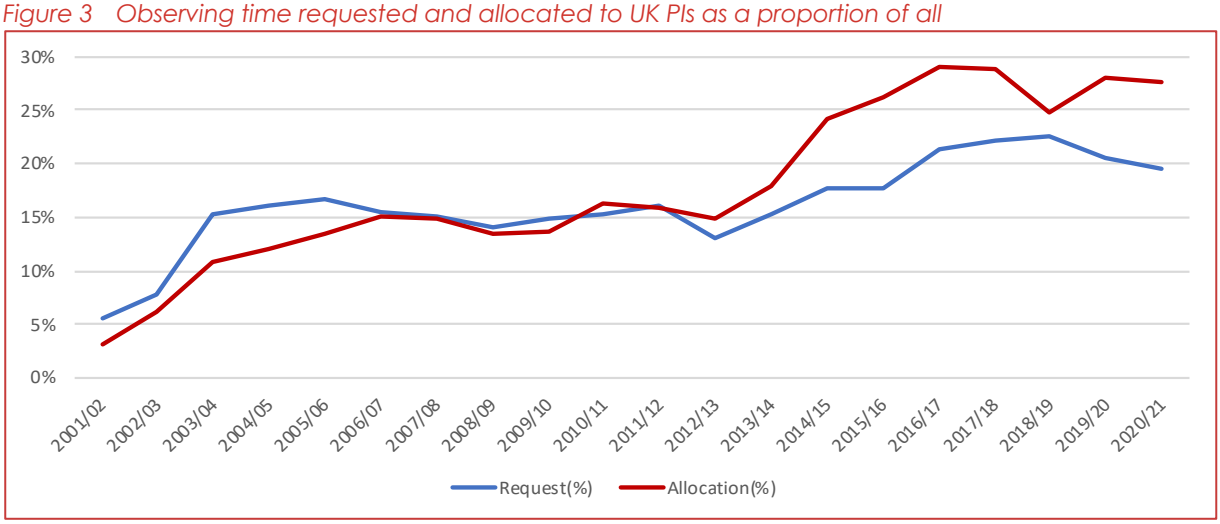
Interviewees also noted the value of ESO's capacity to host visiting instruments, which allows innovative technologies and instruments to be added relatively easily for short periods of time. For example, the ULTRACAM (developed and designed by the Universities of Sheffield and Warwick and the STFC's UK Astronomy Technology Centre) was installed on the Very Large Telescope (VLT) in 2005, allowing for the study of the very faintest stars at the very highest speeds. As a result, scientists were able to study the GU Muscae; a black hole in a 10-hour orbit with a normal star which produces flares as material falls into the black hole.

The UK's scientists and engineers in research laboratories and universities have been heavily involved in ESO instrument development since joining (with national funding available to support this significant involvement), meaning it is well placed to take advantage of these new instruments once they are installed. The UK is also a sought-after partner for subsequent research collaborations, based on knowledge and understanding of the instruments in place – generating research opportunities and funding for years to come.

The UK is very active in its use of ESO, and our survey demonstrates the breadth of the UK community benefiting directly; respondents came from 37 different institutions (including 29 universities, plus other centres, laboratories, observatories and facilities around the country).

ESO normally receives ~2,500 research proposals each year for use of telescopes, with requests for 4-6x more nights than are available. Around 15-20% of these proposals tend to come from a UK Principal Investigator (PI) (Figure 3). The UK has also achieved above average success rates in applications for observing time, and as a result, the number of nights allocated to UK PIs has been increasing over time (with e.g. UK PIs securing 29% of all allocated time in 2019/20). There is no guaranteed time set aside for each member state, so the UK has performed well, even compared to its relatively large share of subscription fee contributions (~17%).

Figure 3 Observing time requested and allocated to UK PIs as a proportion of all



Source: ESO. Data collated on request of the study team.

The process to allocate time on ESO telescopes (other than ALMA) is decided solely on the basis of scientific excellence and a ranking of proposals and, while time can be allocated to non-ESO member state institutions, these requests must meet a more demanding set of criteria. Specifically, proposals where two-thirds of the team are from non-ESO member states must be 'scientifically outstanding', require instrumentation / telescopes not available at any other accessible observatory, and not be similar to ESO member state proposals. ESO statistics on the distribution of telescope time show that, as a result, the great majority of allocated time goes to applicants in member countries (some 60% to 85%, depending on the telescope and period), with another 10-20% generally allocated to ESO and applicants from the host state of Chile. Membership does therefore provide strong additional value in terms of UK access to facilities and the research-related benefits that flow from this.

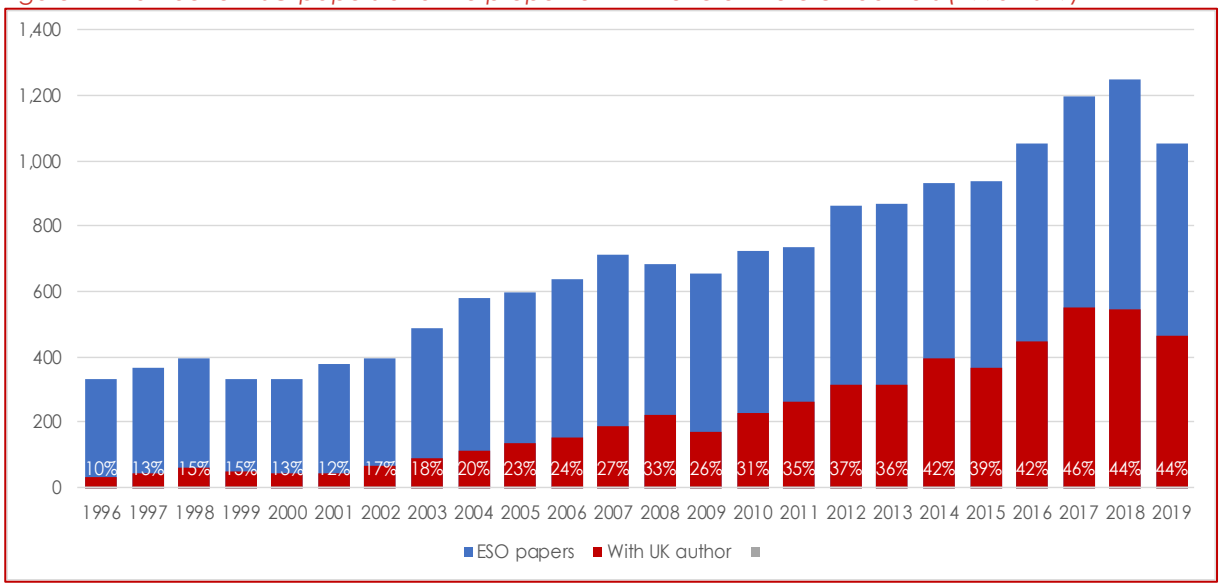
The survey of the UK astronomy community, conducted as part of the study, asked about the potential implications in this area of the UK not being a member (including the likelihood that they would be awarded access to an observatory, or to the same or similar instruments elsewhere). Respondents were also asked about the implications of this for pursuing the same research questions or areas. Just one quarter (26%) thought it likely that they would be awarded access to another observatory without ESO, while the vast majority (95%) reported that it was unlikely (or more often, very unlikely) that they would be able to access the same or similar instruments elsewhere. As such, around two-thirds also stated that, were the UK no longer a member of ESO, it is likely (or very likely) that they would pursue a different research question, while 39% went further to say that they would pursue a different area of research entirely.

STFC's Astronomy Advisory Panel survey of the astronomy community (recently conducted as an input for the STFC Astronomy Evaluation) provides further supporting evidence. This found

that continued membership of ESO and access to its facilities was the highest priority for this UK research community, given its criticality for their research activities in the forthcoming years.

The opportunities and access afforded by **ESO membership helps the UK continue to play a leading role in advancing understanding.** Examination of ESO papers (publications that use data from ESO facilities, in part or entirely) shows that the number of ESO publications in the astronomy and astrophysics subfield with at least one UK author increased from 272 in the six years prior to membership, to 741 in the first six years of membership (and to 2,724 in the most recent six year period). This more than ten-fold increase (from first to last period) well exceeds the growth seen in UK astronomy and astrophysics publications more generally (a less than three-fold increase over the same period). Similarly, the share of ESO publications with at least one UK author has also increased significantly over the same time span (see Figure 4), from 13% in the six-year period pre-membership to 43% in the most recent six-year period, passing the rates achieved by several founding members (e.g. France and Italy).

Figure 4 Number of ESO papers and the proportion with one or more UK authors (1996-2019)

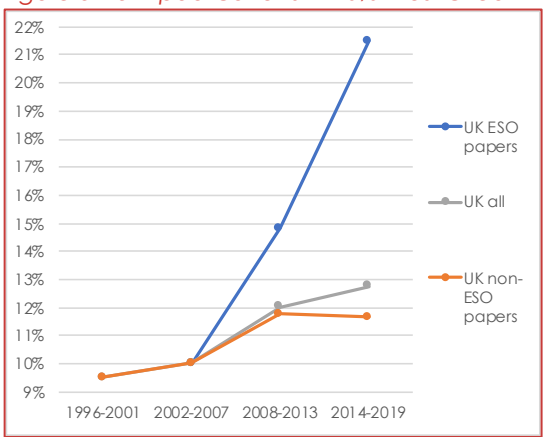


Source: Technopolis / Science-Metrix, based on Scopus Data. Full counting method. 2019 incomplete.

ESO also **supports the strength of the UK research community** and its scientific achievements and progress, helping to sustain the UK as a world-leading research nation.

ESO-affiliated publications have been found to pull citation metrics upwards in the UK, providing an indication of the high-quality research enabled. The proportion of the UK's papers in the astronomy and astrophysics subfield in the top 10% most cited globally has been increasing steadily since it joined ESO (see Figure 5). It is difficult to maintain a very high impact as production volume goes up. As such, the UK's combination of high output and high (and improving) citation profiles in the astronomy and astrophysics subfield since the UK joined ESO is a strong achievement.

Figure 5 A&A publications in 10% most cited



Source: Technopolis / Science-Metrix

Most survey respondents claimed that ESO had been significant or critical for the strength of their international networks and ability to collaborate with other members, while 25% went as far as to claim that ESO was critical to the very existence of their group or department. Most respondents (78%) also claimed that the UK's involvement in ESO was significant or critical for attracting top scientific and engineering talent to the UK. The 2016 Royal Astronomical Society survey of the UK astronomical community seems to support these results, with over half of respondents to this exercise originating from outside of the UK.

> *"Without ESO membership, a good fraction of [the UK's] academic astronomers would be unable to pursue their research, and many of the most active and highest-profile would undoubtedly seek positions abroad." (Respondent to survey of UK users)*

Box 2 Case study – Next Generation Transit Survey

The Next-Generation Transit Survey is a purpose-built observing facility located at ESO's Paranal site. Intended to search for transiting planets on bright stars, the instrument and its enclosure was designed and built by a consortium of UK, Swiss and German research groups and institutes. From the perspective of the project team, the success of NGTS would not have been possible without the UK's membership to ESO. Because the UK is a member, the consortium was able to secure access to the site and benefited from ESO's in-kind support and resources which allowed the project to proceed within budget.

In building the instrument, the consortium team worked with UK companies to provide components. Andor Technologies developed the camera equipment for the instrument, optimising an existing product to meet the extreme accuracies required and as a result have produced a new camera product and deployed improvements to the stability of their CCD cameras across their product line. GR-Pro, a precision manufacturing firm designed and fabricated a new robotic enclosure for the NGTS instrument. In designing and delivering the enclosure, GR-Pro gained more experience of the complex engineering required to meeting the design challenges, as well as experience of exporting goods internationally. GR-Pro are now taking the concepts and designs developed for this project into other markets.

Since it began operating in 2016, the NGTS team have discovered 24 new exoplanets, resulting in numerous publications. The project has made important contributions to building UK strength in exo-planet research and strengthened UK success in securing observing time at ESO. As a result of NGTS, Professor Pollacco was appointed science coordinator for ESA's PLATO mission and the expectation is that the researchers trained on NGTS will be exploiting PLATO when it is launched in 2026. This demonstrates how ESO membership, by enabling the NGTS project's success, is supporting the development of capability and expertise to capitalise on the UK's investments in astronomy research.

Interviewees also highlighted the UK's success in securing European Research Council (ERC) funding, with access to ESO forming the basis for many successful ERC bids and therefore the leveraging of European funding. ERC grants are widely seen as a benchmark of excellence in any field, and so the UK's high number of awards here (the UK accounted for one-quarter of all ERC grants in the Universe Science domain, 2007-20, despite the scheme being open to all EU Member States and Associated Countries) is an impressive achievement and a strong indication of the strength of the UK community in astronomy, astrophysics and related fields.

It is difficult, if not impossible, to attribute an economic value to all of the research undertaken at ESO, since it contributes to the advancement of knowledge and flow of ideas, which may only materialise into socioeconomic benefits indirectly, and in the longer term. As such, these benefits do not have market prices that can be used to express them in monetary value. We have however, employed two approaches that attempt to attach monetary values to some of the research-related benefits of ESO (see Section 3.6)

3.3 Benefits relating to world-class innovation

ESO cooperates closely with European high-tech industries, research institutes and centres to provide ever-better astronomical telescopes and instruments. In 2019, for example, ESO invested 60% of its budget in the design and construction of telescopes and instruments, with over 90% of this invested in high-tech innovation led by industry and research institutions in Member States. As a result, ESO has supported the development of a wide range of novel technologies, including active and adaptive optics, laser frequency combs and sodium lasers, Shack-Hartmann wavefront sensors and time reference systems, to name a few. Such technological advances have then made large telescopes such as the VLT and ELT possible.

These technologies also constitute new or improved products, which can then be sold or shared more widely, to other research facilities and beyond – even coming into more general use and affecting areas of UK life that are far-flung from the original ESO purpose. New applications underpinned by technologies developed at / for ESO could also deliver societal impact by bringing these benefits to, for example, UK consumers, patients or the environment.

Our interviewees often pointed to the **translation and application of software technologies** developed for interpreting and processing astronomical research, as examples of such spill overs, as well as to emerging opportunities around AI and machine learning for image processing in a range of applications.

They also highlighted **ESO developments in adaptive optics** as an area of strong potential for future translation. UK researchers (e.g., at UK Astronomy Technology Centre and the University of Durham) are developing strong expertise in this field and are exploring applications of adaptive optics in microscopy, with future potential in satellite communication. The UK's involvement with ESO supports the development of this research and offers opportunities for future collaboration and development. As such, once commercial applications are found, the UK will be well placed to exploit this.

ESO innovation is being applied for diagnostic and therapeutic purposes in the UK

Astronomical codes for detecting cancer

A large part of astronomy depends on the detection and analysis of light, and (despite the vast differences in scale) the process is very similar when analysing light travelling through the human body. The University of Exeter is therefore applying techniques developed by astronomers to detect breast cancer (which creates tiny deposits of calcium in tissue that can be detected though changes in the wavelength of light) and to improve the treatment of skin cancer (using light-activated drugs and light-heated nanoparticles).

Astronomical AI for observing changes to moles

The algorithms used to detect exploding stars within astronomical images are being tested by the University of Southampton as a tool to spot changes in moles on the body, thereby detecting potential cancerous growths sooner. Only by comparing multiple images is it possible to discover the presence of a supernova (or a cancerous mole in this case). Deploying advanced AI and computer modelling, the team hopes to make this process simple and easily accessible to dermatologists.

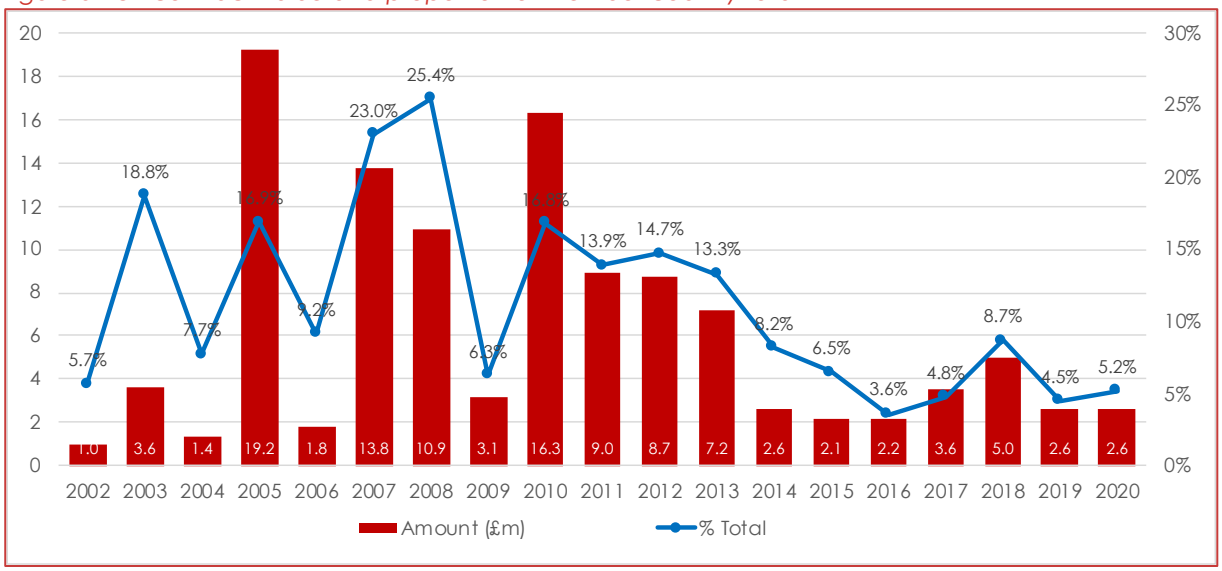
ESO also engages with suppliers through procurement contracts that in many cases entail the development of innovative products, services and technologies. These can be quite specialised and require a degree of innovation, with further improvements and modifications needed to cater for the demanding requirements of cutting-edge research.

Membership provides UK companies with preferential access to ESO contract opportunities, with £1bn-worth of contracts issued (overall, to any country) in the last decade alone. Available procurement data from ESO shows that at least 258 different UK organisations have been involved in successful bids to ESO over the past 16 years (2004-2019).

Most commonly these UK contracts have related to insurance, optical imaging detectors and large optics, but there have also been UK contracts in a range of other categories, including filters, software, civil engineering, cryogenics and consultancy.

Awarded contracts bring direct additional revenue to UK organisations and support employment (industrial return). The UK has secured £117m[2] in ESO contracts between 2002 and 2020, representing 12.2% of the value of contracts across all ESO Member States. In some years the UK has performed better than this average, and in particular it secured 23% and 25% of the total awarded to all Member countries in 2007 and 2008 respectively (see Figure 6 below).

Figure 6 UK contract value and proportion of Member country total



Source: ESO procurement data, based on payments by country of origin

ESO has a clearly stated preference for procuring from member countries, and seeks to do so wherever possible. It does typically spend 30-40% of its annual budget outside the member states, but more than 90% of this is accounted for by Chile, which hosts its facilities. Only a small proportion of spend is then spread across other non-members (in areas where no Member State is available). The USA is the main external recipient, and it tends to only realise around 2-3% of the total value of ESO contracts being awarded. Other non-members are negligible in the statistics. As a result, the amount awarded to UK contractors in the past thirteen years (2008-2020, the period for which detailed country breakdowns are available) is more than double that awarded to the USA, despite that economy being seven times the size.

If the UK were to perform similarly to the USA (as a non-member, taking account of the size of the economy), then it might hope to achieve ~£500k in total each year from ESO contracts, rather than the ~£6m per year actually realised as a Member between 2002 and 2019.

Scientists and engineers from Member States can also join consortia developing ESO scientific instruments, usually receiving guaranteed observation time in exchange. The costs of these projects are largely covered by the Member States, but the opportunities for involvement (and the skill and capability benefits that this can bring) are provided by the UK's ESO membership.

[2] Amounts shown in this section have been converted EUR to GBP based on the average exchange rate each year.

UK suppliers also realise wider benefits, beyond the direct financial value of the ESO contract itself, including (most commonly reported through our supplier survey) new knowledge and capabilities gained, higher staff satisfaction, and access to new contacts. ESO is also a highly reputable organisation, with contracts bestowing credibility and prestige on the businesses concerned. Most of the UK suppliers to ESO that we surveyed (79%) reported seeing an increase in their reputation or brand value as a result of working with ESO through past contracts.

One of the main reported motivations for bidding for ESO contracts is the possibility of further contracts, either with ESO or with other research facilities, off the back of a successful ESO contract. Around 40% of the UK supplier firms we surveyed said that past ESO contracts had already resulted in an increase in sales income (beyond any additional ESO contracts).

We have explored an approach to measuring the additional value to UK suppliers of access to ESO contract opportunities (i.e. beyond the value of contracts themselves) in Section 3.6.

Box 3 Case study – Observatory Sciences Ltd.

Observatory Sciences Ltd is a small UK-based company that provides software control systems for large scientific research facilities. After contributing to the development of the VISTA telescope in 2002 and building relationships within ESO, the company secured three consultancy contracts to support the design of the ELT's software systems.

In 2017, the company also won a contract to provide software maintenance services for the VLT and VLTI, valued at up to €1m. The contract entails providing bug fixes, as well as developing enhancements and new software modules for the VLT Common Software Infrastructure (which is used for operation of all telescopes and all instruments at the ESO observatories). The contract accounts for ~25% of Observatory Science's business and allowed the company to grow and employ four new, highly skilled staff.

The contracts have also provided Observatory Sciences with valuable insight into an exemplar software system, as well as an important endorsement of their services, which is expected to support the international competitiveness and saleability of their services in the future.

Box 4 Case study – Teledyne e2V

E2v, now part of international company Teledyne e2v, based in Chelmsford in the UK, has been providing high sensitivity Charge Coupled Devices (CCDs) image sensors for ESO telescopes for many years. This includes delivering CCD detectors and infrared detectors for different instruments, adaptive optics modules and early-stage design studies. Many ESO telescope instruments use their technology, including VLT's SPHERE, VLT Adaptive Optics Facility, ERIS, CCD image sensors (4k x 4k) on MUSE, ESPRESSO and sensors on NGTS, as well as infrared detectors for the HARMONI, MICADO, METIS instruments. Fast low noise CCD (CCD220) developed by Teledyne e2v and development funded by ESO for Adaptive Optics applications became a reference on this market and are a central component in scientific commercial cameras produced by the French company First Light Imaging and others.

When ESO first began working with e2v in the 1970s, it was one of many players trying to get a foothold in the market. Today, Teledyne e2v is the world leader for supplying specialised CCDs for scientific and medical applications in a market (the CCD image sensors market) valued at US$1.82 billion in 2019 and is expected to reach US$2.60 billion by 2025. Although the success of e2v cannot be attributed to ESO alone, ESO worked closely with the company to support the early development of many of these technologies and continues to do so today.

For example, in 2004, e2v began a long programme of work for developing large CMOS (Complementary Metal Oxide Semiconductor) detectors for the E-ELT and in 2017, Teledyne e2v was awarded a multimillion-euro contract to design and manufacture 28 Large Visible Sensor Modules. These sensors, to be manufactured at the Chelmsford site, will feed into the telescope's adaptive optics systems to ensure the image stays in sharp focus in spite of atmospheric fluctuations.

Box 5 Case study – Glyndwr Innovations

A UK consortium involving Glyndwr Innovations (wholly owned by Glyndwr University in Wales) was contracted to deliver half of the prototype mirror segments to be deployed on ESOs planned E-ELT.

The contract required a step change in the speed and precision of mirror manufacturing, and the team developed a unique polishing and measuring system to meet necessary tolerances (and in a much-reduced time). Using computer-controlled polishing, they also became the first in the world to polish a hexagonal mirror element to the edge (necessary for a combined mirror of 39m diameter, made up of individual segments). The company also greatly increased the size of mirror that it is capable of polishing.

Glyndwr Innovations has been able to leverage their work for ESO and expand their precision optical and components business, such that they can now research, design, manufacture, and install their optical systems. Around 30-40% of their turnover continues to come from ESO contracts. However, since the telescope market is not extensive, the team has also moved into other markets, for instance developing lightweight telescopes for high-altitude Unmanned Aerial Vehicles for earth observation (for the Ministry of Defence).

The work for ESO acted as a critical launching pad for the business, bringing important prestige to both the University and Glyndwr Innovations, which has continued to serve it well to this day. The company has already grown from nothing to a £1.5m-£2m a year business, employing up to 14 staff, within the space of a few years. It has also become a useful model for other Glyndwr University endeavours.

Box 6 Case study – Leonardo

Leonardo's Infra-red Detection department, based in Southampton, is the world leader in the design, development and manufacture of a wide range of infra-red detectors.

Though Leonardo first worked with ESO in the 1980s, they were not active in the astronomy market for almost 20 years until they were approached by ESO scientists in 2007 to develop a wavefront sensor for adaptive optic systems for the VLT GRAVITY instrument. Through this programme, Leonardo developed the SAPHIRA detector, a unique and extremely sensitive detector which has supported several groundbreaking observations, including research characterising the supermassive black hole Sagittarius A*, which received the Nobel Prize for Physics in 2020.

As a result of their work for ESO, Leonardo have re-entered the astronomy market and SAPHIRA has since been deployed in 9 major telescopes internationally. The SAPHIRA detector has also been baselined for space applications, including for use on future NASA and ESA missions. Leonardo are now working with ESO, the Canadian National Research Council and the Max Planck Institute for Extra-terrestrial Physics and the Leibniz Institute for Astrophysics Potsdam in Germany to develop a larger SAPHIRA array for the European ELT and will supply the detectors for the HARMONI and METIS instruments. The SAPHIRA device has also been commercialised in non-astronomy markets and is a central component in scientific commercial cameras produced by the French company First Light Imaging.

Though Leonardo's contracts with ESO typically amount to less than 1% of their business, these have facilitated work and contracts in the astronomy sector more widely, amounting to 5% of their business. Their collaboration and contracts with ESO have also supported Leonardo to attract and retain staff, and gain valuable expertise and knowledge with potential benefits to their other areas of business.

3.4 Benefits relating to world-class skills

ESO offers a wide range of training and skills development opportunities, including through its direct or indirect interactions with UK suppliers and users, as well as with trainees and students. These opportunities are predominantly available to individuals within ESO Member States.

For example, the ESO Fellowship Programme (a post-doctoral research programme for astronomers to do independent research) is open to all, but with a preference for member state nationals. Similarly, the ESO Studentship Programme (which seeks to connect PhD students and their advisors with ESO and the ESO community) is offered first to those enrolled in a university PhD programme within an ESO member state. There have been around 80 UK ESO Fellows and students in total (based on their first nationality) since the UK became a member, which represents about 10% of the total number during this period.

Most of the surveyed UK user community reported that ESO involvement had had a significant or critical impact on their ability to work in an international environment and on their experimental skills, as well as in relation to their team working, project management, communication, computing and problem-solving skills. Similarly, respondents that had been employed directly by ESO (including via the Fellowship and Studentship programmes) most commonly reported significant impacts from their ESO experience on their technical research skills, their international networks and connections, and their reputation and employability. It was also clear from our consultation that many in the UK had built their careers around working with ESO data or developing instrumentation for ESO.

> *"I have acquired a deep understanding and knowledge of the Science Data Archive and of the instruments and observing facilities available at ESO. This made it easier for me to apply for observing time and to plan the observations, but also made me realise that a lot of science can be carried out with already existing publicly available data."*
>
> *"The ESO fellowship program lets the fellow develop their own research in the context of the best observational facilities in the world. Europe has no other scheme like it (UKRI fellowships are aimed at a more advanced career phase). It has been the basis of my scientific career."*
>
> (Respondents to survey of UK users)

The knowledge and skills gained through ESO can then be deployed more widely in the UK economy. It was regularly mentioned by interviewees that those with ESO experience are highly sought-after, both in- and outside of astronomy and academia. As an example, several pointed to their students taking programming and data mining skills (developed through ESO) into areas as diverse as finance, remote sensing, human behaviour analysis and meteorology.

ESO, its Member States, users and the media also disseminate and reach out to the UK public, celebrating achievements at ESO and thereby raising its profile (as well as that of astronomy and science in general). Through the study consultations, ESO was regularly commended for the large quantities of useful and high-quality materials produced for both the media and for teaching purposes. Its work with supporting science communicators and through the ESO Science Ambassadors initiative were also both highlighted by UK stakeholders as good examples of ESO's important role in expanding interest in STEM careers, while simultaneously promoting ESO in the wider community. In 2018 alone, the ESO Ambassador project delivered two Q&A sessions for early-career researchers in the UK, ran workshops at two city science festivals (Manchester and Durham) and donated ESO Supernova equipment for UK schools.

Country-specific data on ESO-based public outreach is limited. However, available statistics do show significant engagement with the UK public. For instance, there are 8,219 UK-based followers of ESO on Facebook (May 2020) and there have been 605,000 UK-based views of ESO material on YouTube (2007-2020). ESO also recorded over 300,000 unique UK users of its main website in just the four-year period 2016-19. Finally, nearly 10% of the registered users of the ESO

Science Archive (where the UK is the most active user country) do not belong to the category of professional astronomers (which includes students and post-docs), indicating a community of amateur astronomers who are accessing this data, including within the UK.

Nearly all respondents (95%) to our survey of the UK science community indicated that they use ESO materials in their own outreach activities. This includes using ESO images, data and other materials for public events and talks, school visits, student events, radio interviews, open nights and presentations to various societies ang groups.

> *"We routinely use ESO data in our public outreach, e.g. the monthly open nights at our university observatory from October to March, our mobile planetarium visits to schools and recently to large music festivals around the country."*
>
> *"An image we created in part from ESO Public Survey data was picked up in a news story that was the Most Viewed and Most Shared item on the BBC News website. It elicited many comments extolling the virtues of science and highlighting the UK's role in cutting-edge research."*
>
> *"We run a substantial outreach and public engagement programme which interacts with ~10K members of the public annually, split between school children, youth groups and adults. These activities are threaded with ESO-enabled research that inspires the next generation of scientists. Our activities are especially targeted at raising the science capital of disadvantaged communities and young people."*
>
> (Respondents to survey of UK users)

These various dissemination and outreach activities relating to ESO, undertaken by institutions and individuals will all help to increase the UK public's appreciation of science, awakening interest in ESO, the science that it supports and the outcomes and benefits of this work, including amongst young people and the next generation UK workforce. A majority of the UK community polled said that ESO's contribution was particularly significant within the wider mix of efforts to increase UK public understanding and support for science and engineering

3.5 Benefits relating to science diplomacy

ESO is visible internationally and acknowledged as a leading centre of scientific research. The UK's membership provides it with international visibility, enhances its network of connections, nurtures its perception as a great science and innovation nation, and contributes in some measure to favourable perceptions of the UK as a country to partner with or invest in.

ESO membership allows greater UK involvement in different aspects of ESO governance (decision making bodies, staff, users). For instance, despite being a relatively new member, the UK currently holds two of the five top ESO jobs (Director of Science and Director of Programmes) and accounts for 6-7% of all ESO staff members and Fellows, or around 50 people. The UK also has representatives on the Council, the Science and Technical Committee, the User Committee, the Finance Committee and the Time Allocation committees (which rank proposals), amongst others, helping to define what scientific excellence is for Europe.

This involvement in ESO provides the UK and its science base with a platform for international engagement, leadership and agenda-setting. Benefits may include better sight of the strategic direction and priorities of other countries, as well as some ability to influence ESO decision making (funding and priorities), thereby enhancing alignment of ESO activities with UK needs, capabilities and priorities. As a result, the UK may benefit from a better 'fit' of resulting opportunities and activities for its research community and companies.

There are undeniable benefits of being a member and 'sitting at the table' where decisions are being made today about the future of astronomy 20-30 years from now, as this allows the UK to influence research agendas and be at the forefront of future developments.

These are important aspects, but difficult to quantify or monetise. The extent to which such benefits exist, and the extent to which they are of value, was therefore explored qualitatively by the study through consultation. For instance, nearly all survey respondents (96%) claimed that ESO's priorities and activities were very / well aligned with the interests and capabilities of the UK. The great majority (75%+) also argued that UK membership of ESO has large or critical effects on the UK's international presence and visibility within the scientific community, the weight of its views on science and research matters, and its ability to influence international research, science and technology priorities.

ESO also provides a platform for international collaboration and exchange and actively encourages international, political and cultural understanding. This occurs through different means and at different levels, including through joint investment and decision making, joint research and development (multi-country teams of researchers, scientists, businesses), and by providing a neutral space for wider diplomacy, interaction or discussion.

ESO is also engaged in a number of strategic partnerships with other international organisations, which creates links with countries beyond ESO's direct Members. This includes through ALMA (with North America and East Asia), collaborative agreements and programmes with Chile, cooperation with the European Space Agency (e.g. UK-led Gaia-ESO public spectroscopic survey, the International Asteroid Network, and annual joint workshops and Fellowship programme), coordination with CERN and hosting part of the Cherenkov Telescope Array (under construction, involving a consortium of over 1,500 members from 200+ institutions in 31 countries).

3.6 Costs and (monetised) benefits of the UK's investment in ESO

Costs: ESO's budget — used for construction, maintenance and operation of observatories, plus 700 staff — is made up almost entirely of subscription fees from Member States. Annual contributions total £165m (2020 figure), with each country contributing in proportion to their national income. The UK (via STFC) is currently the second largest contributor, after Germany, paying 17% of fees in 2020 (~£28m)[3]. This equates to 4% of STFC's total budget. **Over its 19 years of membership (2002-2020), UK contributions to ESO have totalled £432m, or £22.7m per year on average (2020 prices).**

In addition to the annual contribution, there have other one-off costs over time:

- An accession fee, to reflect the past investment made by existing members in the current facilities. The UK paid £185m (2020 prices), in cash and in-kind, spread over a decade
- A one-off additional contribution for the Extremely Large Telescope (ELT) construction programme. The UK contribution was £41m (2020 prices), paid between 2013 and 2017

Monetised benefits: Government guidelines (HMT Magenta and Green Books) advise also giving a monetary value to impacts wherever possible, while other benefits should be recorded (and quantified in another way, to give a sense of their magnitude). However, monetising the impact from Research Infrastructures is a challenge for all evaluators and funding bodies, as not all identifiable benefits to the UK from (in this case) its investment and involvement in ESO are monetisable.

[3] This includes an additional (annual) top-up fee for the construction of the Extremely Large Telescope (ELT). This adds ~2% year-on-year to the annual subscription from 2014 until 2023 (and will remain flat thereafter to cover operational costs). The costs so far (2014-20) of this element to the UK has been £18m (2020 prices).

Nevertheless, where there was sufficient data and a robust approach available, we have attempted to capture and assign a value. This includes:

- £14.6m per year - The income-in-kind monetary value of ESO telescope time awarded to UK academics (based on award data and ESO costs, used by STFC for REF submissions)
- £19.2m per year - Estimated value of knowledge production itself (using UK ESO publications data, combined with other information on researcher time and salaries)
- £11.6m per year - The willingness to accept (WTA) of UK suppliers to forego access to ESO contracts (based on supplier survey), which provides an estimate of the intrinsic monetary value of access and the additional value to suppliers beyond the contracts themselves (e.g. benefits reaped elsewhere from the developments supported by ESO)

Based on these three areas of benefit, we have arrived at a total of £45.5m per year in *monetised* benefits for the UK (2020 prices).

This is very much a minimum value for the benefits derived from the UK's investment in ESO. It does not capture the full range of impacts emerging from access to the facility, which are explored (but not monetised) in the study and summarised in previous sections. This includes, for instance, the contribution of ESO to the advancement of knowledge, the translation and application of technologies developed for ESO in other fields (e.g. astronomical codes being used to detect cancer), or the benefits to the UK of sitting at the table where decisions are being made today about the future of astronomy 20-30 years from now.

3.7 A future monitoring and evaluation framework

As part of the study, an outline proposal has been prepared for an updated monitoring and evaluation framework for STFC to use as the basis for tracking the benefits flowing from the UK's subscription to ESO in future. The framework (which is set out in Section 13 of the Evidence Document that accompanies this Summary Report) is also designed to support independent evaluations that STFC may wish to commission in future, to ensure a wide-ranging and robust assessment of achievements across each of the four principal impact pathways.

The experience of conducting this study has uncovered gaps in the available evidence base, as well as several data and methodological challenges that need to be addressed or at least improved. To that end, we have suggested the current monitoring system could be strengthened with the addition of several new periodical data collection exercises, including surveys of UK suppliers, researchers and the general public, plus regular bibliometric analyses and improved cataloguing of achievements.

The estimated costs of these additional activities are likely to go beyond current levels of resourcing, but they are not an unreasonable ambition, given the scale of public investment involved. The new and enhanced monitoring and evaluation activities will help to identify, quantify and monetise more of the total spectrum of impacts than was possible within this evaluation, enabling a more complete account to be given of the benefits being derived from the UK's investment and involvement in ESO.

4 Key findings from the process evaluation

STFC plays an important role in promoting opportunities for UK companies to win commercial contracts from international science facilities, ensuring a return for UK businesses from the government's global investments. To further support this, it commissioned a process evaluation as part of the current study, including an assessment of UK achievements (return) to date and an exploration of the challenges and barriers faced by UK companies in bidding successfully for ESO contracts, in order to arrive at a series of recommendations for improving UK return.

4.1 UK industrial return from ESO

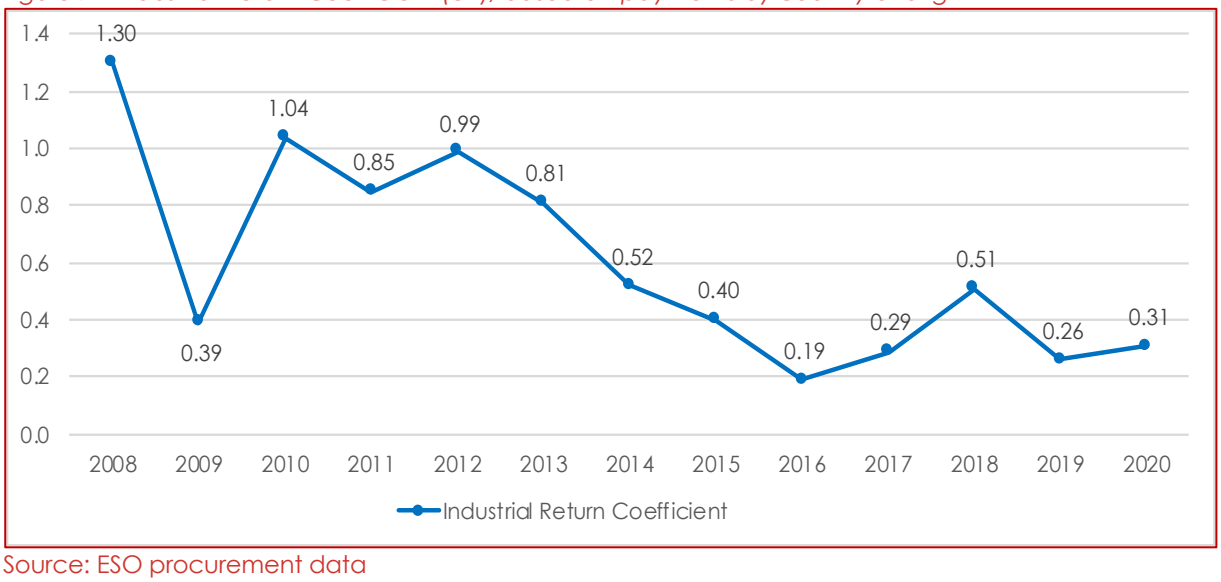
As explained in previous sections, ESO membership provides UK companies with preferential access to contract opportunities that can bring additional revenue, employment, skills and other benefits for the individuals and organisations concerned within the UK.

ESO procurement data shows that the UK secured £117m in ESO contracts between 2002 and 2020 (£6.1m/yr). This is 12.2% of the total going to all member states during this time, and is lower than the share of member subscriptions that the UK contributes (17%-21% during this period). This UK share of contract value appears lower if one also includes payments to Chile, the US and other non-members, whereby the UK proportion drops to 7-8% overall for 2002-20.

There is considerable variability between years, however, and payments to the UK have varied between £1m and £19m per annum (while its share of Member payments has varied between 4% and 25%), with results heavily influenced by a small number of individual contract wins, and whether ESO is in a 'build' or an 'operations' phase (in the latter, spend is more focussed on operations, where proximity can be more important). Nevertheless, the general trend has been downward over the past decade (both measures), with some small exceptions.

As a result, the UK's Industrial Return Coefficient (IRC, which compares the share of contracts to the share of subscription fees) has also tended to decline over time. A coefficient of 0.7 or above is considered 'good' and this has not been achieved since 2013. In fact, for three of the past five years, the UK has achieved a coefficient below 0.3, which is classed by ESO as 'poor'.

Figure 7 Industrial Return Coefficient (UK), based on payments by country of origin



Source: ESO procurement data

The UK's IRC over the past decade places it mid-rank amongst members (just below the indicative 'good' rate of 0.7)[4]. Cross-country analysis also suggests that length of membership may play a role in achieving a good return, whereby longer involvement may have helped suppliers to develop stronger links and to better learn / adapt to ESO procurement processes.

There is limited data available on past UK bids to ESO as there is no automatic feedback from ESO to the UK on the actual number of replies or bids eventually received from companies. However, internal STFC analysis suggests the number of UK responses to tender opportunities varies enormously depending on the tender in question. General IT hardware or support and custom electronics have tended to result in large numbers of interested companies, while other more specialist items receive few responses, if any.

4.2 The UK Industrial Liaison Officer (ILO)

To support the procurement process, ESO maintains a supplier database and UK suppliers can register with this database directly through ESO's website, or through the UK Industrial Liaison Officer (ILO). ESO also presents short- and medium-term procurement opportunities at the annual ILO meeting, giving ILOs the opportunity to identify relevant companies well ahead of tender and introduce them to the ESO procurement team.

The UK's ESO ILO is responsible for contributing to a database of potential suppliers (which covers all STFC large facilities), running engagement events and communicating ESO contract opportunities. The role was, until April 2020, based at STFC's UK Astronomy Technology Centre and delivered by the UK's ELT programme manager. The co-location of the ESO ILO with the ELT team had been a strategic decision to support stronger links between suppliers and the ELT procurement process. However, since much of the ELT procurement has now been commissioned, the role has been transferred to STFC's central Business Opportunities Team.

4.3 Supplier experience – barriers to (successful) bidding

In the survey of UK suppliers undertaken for the study, over half (58%) of the 78 respondents had bid (successfully and / or unsuccessfully) for ESO contracts in the past, often on more than one occasion. These organisations, as well as those that had not yet bid to ESO (but had bid to other national or international science facilities) were asked about the challenges and barriers.

Key issues that were commonly raised included:

- Limited awareness of procurement opportunities, or lack of sufficiently advanced warning
- The nature of ESO contracts available, which are often large and complex, exceeding the financial, technical or administrative capacity of many individual (particularly smaller) companies, and acting as a barrier to entry for new firms
- The price sensitivity of ESO procurement, creating difficulties for UK companies to price competitively, but also leaving little room for profit (incentive). (Although it should be noted that in 2019 ESO moved from 'lowest cost compliant bid' to 'best value for money', which may not be fully reflected in the feedback)
- The challenging or unattractive terms and conditions of ESO contracts, including value-to-turnover requirements, the need for bank guarantees, issues around IP ownership, and payments tied to design gates - all of which reduced the incentives to bid
- The administrative requirements, which can be substantial, and daunting for the uninitiated

[4] The ESO procurement data used for this analysis is confidential and cannot be made public. We can therefore only provide limited information on the UK's relative position.

Nevertheless, a majority of surveyed suppliers (successful, unsuccessful and non-bidders) reported that they would be interested in bidding for ESO opportunities in future. This was because of the potential to support the growth of the company, the opportunity to enter a different market and the prestige of working with ESO in particular.

When asked what might support or encourage future bidding, most suppliers called for more timely access to information on ESO opportunities (including *upcoming* tenders), giving them the time to explore these with ESO and potential collaborators, as well as the time to prepare a good bid. Linked to this, it was also suggested there was a need for more awareness (within STFC / ESO) of potential supplier competencies, so as to notify them of relevant opportunities.

A majority said they would also find it very useful to have:

- One-to-one meetings with ESO (prior to the release of tenders) – both to gain a better understanding of requirements, and to influence these
- Detailed guidance documents and support with bidding to ESO – and in particular, help to understand requirements and ensure compliance
- And communication events (on potential opportunities with ESO)

Most also reported that networking events with UK and international suppliers would be somewhat useful, particularly to facilitate introductions and increase visibility to larger companies. More generally (i.e. from ESO), many UK suppliers would also like to see less stringent qualification criteria and tenders broken down into smaller parts

4.4 Conclusions and recommendations

In April 2020 the UK ILO role was transferred to the Business Opportunities Team within the International User Facilities department of STFC's Programmes Directorate. Moving forward, this will allow the ESO ILO to develop stronger synergies with the ILOs of other large facilities (CERN, ESRF, ILL etc), as well as individuals coordinating and managing the engagement with other international research facilities (ILL, ESRF, European XFEL, and ESS) on behalf of UKRI and BEIS.

Given the timing of this evaluation and consultation activities, there is no evidence yet of the positive or negative impacts of this move. However, insights and lessons from ILOs in other countries indicate that bringing the ILO into the Business Opportunities Team will provide valuable opportunities for stronger coordination and knowledge sharing with other UK ILOs.

Engaging with businesses in relation to broader technology areas (that are relevant to different facilities) provides opportunities for joint and coordinated engagement across the Business Opportunities Team, which could further support efficient, targeted and coordinated engagement. In a similar vein, there is potential to create stronger links with the UK Space Agency's activity to support business engagement with the European Space Agency (as is the case in some of the other countries looked at in the study). The alignment of the technical demands and requirements for instrumentation and the existing business interests in the space sector in the UK could also present interesting opportunities for knowledge and resource sharing, with the potential to leverage existing events, networks and support.

Engaging and supporting businesses to bid for contracts requires sustained proactive effort to connect with a wide range of organisations and to build understanding of the competencies and challenges. Looking across ESO Member States, the amount of time ILOs can dedicate to network building and providing support to companies is often a significant limiting factor for ILOs. Moving the role from the UK Astronomy Technology Centre to the Business Opportunities Team provides opportunities for the ILO to dedicate more time to the role and develop stronger synergies and economies of scale with the ILOs of other large facilities (CERN, ESRF, ILL etc).

Tracking and monitoring business engagement and bidding success provides a valuable resource for coordinating engagement across ILOs and building knowledge of the sector in the UK. In order for the ILO team to better understand and profile their activities, as well as the progress and success of companies bidding for ESO contracts, there is a need for a strong client management tool. The development of this tool is underway, so the next step will be ensuring the details it contains are up to date and relevant. Also, as it stands, it is not clear how much overlap there is between the STFC and ESO supplier databases. This ought to be explored, as there may be companies that are interested in bidding for ESO contracts that are not aware of STFC's role or the availability of support, or companies that ESO is not aware of.

Providing mechanisms for increasing UK companies' visibility and engagement with ESO and its scientists and engineers would be beneficial. In particular, given the value of one-to-one meetings with ESO representatives to support bidding and securing contracts, more could be done to explore how to facilitate this to a greater extent in the future. Further consideration should also be given to the opportunity of hosting ESO industry days, or arranging individual company presentations to ESO, at least in the longer term. A further route for increasing industry contact with ESO directly could be participation in national and international conferences and industry meetings of relevance. Other countries have in the past invited representatives from international facilities (including ESO) to attend, providing a platform for direct meetings.

Finally, businesses could also benefit from more guidance and potentially from financial support for bid development. STFC might consider providing a form of financial support such as a grant or a loan to cover the time and travel costs associated with preparing a bid. The instrument currently employed by CDTI in Spain may prove a useful example, in which organisations are only required to repay the monies if the bid they prepare is not compliant with ESO requirements, or if they are successful in securing the contract.

The Business Opportunities Team is currently in the process of re-defining and re-organising their industry engagement processes and strategy. A specific Action Plan (i.e. strategy) will be developed for ESO along with similar plans for other facilities. As such, the recommendations presented below could provide useful input and guidance for shaping these.

Increasing the UK's industrial return is a long-term goal that is sensitive to changes in ESO procurement approaches. In particular, as most ELT contracts have now been placed, the potential for increasing industrial return in the coming years will be limited.

Given the importance of European collaborations and partnerships in securing ESO contracts, the UK's departure from the EU may also have an impact (e.g. with changing regulations introducing additional barriers and challenges). However, as the situation is still evolving, it is difficult at this time to assess the likely type or extent of any longer-term impact.

There is interest from UK companies in bidding for future ESO contract opportunities, but it may be some time before the UK's coefficient returns to the 'good' levels achieved historically. In the short term (2-5 years), a target of 0.4 would therefore be realistic, as ESO is unlikely to contract large, high-value contracts associated with the build phases, and will be focused mainly on operational expenditure (which tends to favour 'local' businesses in Chile and Germany). In the longer-term, a target of 0.7 is more appropriate (and achievable, as demonstrated by the UK's industrial return prior to 2014).

To achieve these goals, we recommend that the UK's ESO-ILO:

- Continues to work with ESO and other ESO ILOs to identify and improve the accessibility of bidding requirements and terms and contract size and structure, such that they are more accessible to SMEs and/or first-time bidders.
- Provide more guidance documentation to help organisations understand and interpret ESO bidding requirements. Given the overlaps and parallels between ESO bidding requirements and those of other facilities, this could sensibly be developed in collaboration with ILOs for other international facilities where appropriate.

We recommend that the wider Business Opportunities Team:

- Continue with the development of the customer relationship management tool, which should support stronger and more targeted industry engagement. This tool should be used, if possible, to track business participation from their engagement in events through to bidding and final result. The ILO team should also make regular requests to ESO for the final result of tenders below €150k and extract results for tenders above €150k from the ESO website, possibly also following up with UK bidding companies for their feedback. This will also support the ILO team to have a clearer picture of the population of relevant suppliers for any future monitoring or evaluation activities.
- Develop a catalogue of UK companies with capacity and track in securing contracts with Big Science facilities.
- Leverage existing resources and networks from within STFC to build a network of expertise able to provide support to companies if necessary.
- Where possible, identify or co-organise technology or sector specific events through other departments within STFC or other organisations such as the UK Space Agency to raise awareness of ESO tender opportunities, the ILO team and the support available, and further build the contacts database.

We recommend that STFC/UKRI:

- Explore options for providing financial support to organisations to cover the costs associated with bidding for ESO contracts.

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