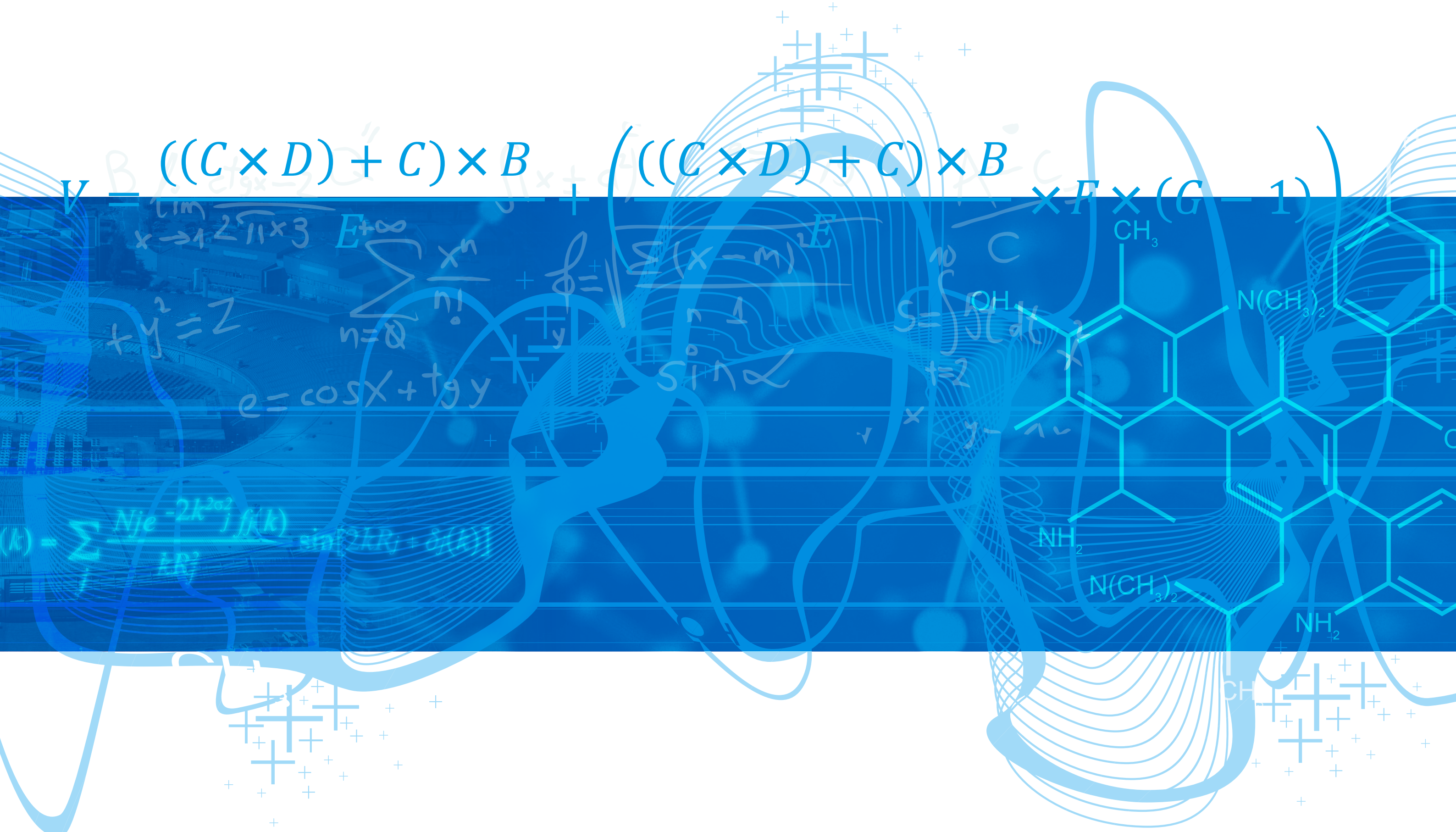
technopolis group

Socio-Economic Impact Study Report

May 2021



diamond

1. Contents

This report presents the main findings from a socio-economic impact study of Diamond Light Source ("Diamond"), which was undertaken by Technopolis in 2018-2019.

It has been compiled by Technopolis in close collaboration with Diamond using evidence to map the impact of Diamond since its creation. Please refer to the appendices for key supporting information.

Authors:

Technopolis: Neil Brown, Charlotte Glass, Paul Simmonds, Cristina Rosemberg, Vivek Seth

Diamond Light Source: Isabelle Boscaro-Clarke, Francois Cesmat, Jonathan Coffer

With special thanks to those who have provided comments and input into this report at various stages in its development, including those who have served on the Advisory Board (or their Deputies). This includes:

Philip	Amison*	STFC/UKRI
Jonathan	Best	Wellcome Trust
Isabelle	Boscaro-Clarke	Diamond Light Source
Neil	Brown	Technopolis
François	Cesmat	Diamond Light Source
Jonathan	Coffer	Diamond Light Source
Henry	Cormack*	UKRI
Sharon	Cosgrove*	STFC/UKRI
Stephanie	Diepeveen	UKRI
Claire	Dougan	STFC/UKRI
Charlotte	Glass	Technopolis
Andrew	Harrison* (Chair)	Diamond Light Source
Chonnettia	Jones*	Wellcome Trust
Fiona	Larner	STFC/UKRI
Hannah	Lockley	BEIS
Jennifer	Moloney	STFC/UKRI
John	Peasland*	BEIS/UKRI
Emily	Richardson*	Wellcome Trust
Alison	Roblin	Diamond Light Source
Dominic	Semple	Diamond Light Source
Vovek	Seth	Technopolis
Paul	Simmonds	Technopolis
Malcom	Skingle*	GSK
Lily	Tozer*	UKRI
Ruth	Williams	STFC/UKRI

**Signifies a member of the Advisory Board or their deputy*

2. Executive summary

This report presents the main findings from **a socio-economic impact study of Diamond Light Source** ("Diamond"), which was undertaken by Technopolis — together with the Diamond team — in 2018-2019 and involved a range of surveys, interviews, case studies and desk-based assessments.

The study set out to measure and demonstrate Diamond's **scientific, technological, societal and economic benefits**, contributing to the available evidence base and serving as an input to future funding requests. It was also to provide recommendations for future monitoring and evaluation efforts, including for any additional data or methods that would be beneficial.

Diamond is an independent not-for-profit organisation, established in 2002 as a joint venture company funded by the UK Government through the Council of the Central Laboratory of the Research Councils at the time (which has become the Science and Technology Facilities Council, STFC) and the Wellcome Trust (who own 86% and 14% of shares respectively). Its primary goal is to deliver basic and applied science together with a 14,000 strong user community generating essential data/information for industry and academia to help address global challenges. Whilst advancing knowledge in many scientific areas, the resulting cutting-edge science also provides significant economic impact.

Since becoming operational in 2007, it has been **a leading centre for synchrotron science on the world stage**, supporting UK academics and businesses to undertake research in a diverse set of areas and sectors. Synchrotrons are one of the most important types of research facility for imaging and non-destructive testing of materials and structures, as well as for the acceleration of drug discovery and development, enabling research that is often not achievable by other means. They also provide unique knowledge for a variety of fields and sectors and are unusual in the breadth of R&D that they support and the range of users they attract. **Diamond is therefore a critical piece of UK national infrastructure.**

To better assess the impact of the facility, the study has used a combination of common and more innovative approaches, using case studies, user estimates of value and other means to estimate the value of some of the benefits already realised. The results are conservative, however, and underestimate the true impact of Diamond, not least because the benefits of past investment and use will continue to emerge for many years to come. Gaps in information, as well as the time and cost challenges of researching all potential impact pathways (in monetary terms) have also inevitably resulted in limited estimates. This kind of study can only ever provide an outline of the impact that such facilities provide.

Overall, however, we estimate that Diamond has so far (2007-2020) had a **cumulative monetised impact of *at least*** £1.8 **billion**, based on the evidence captured at this relatively early stage of the facility's operations. Bearing in mind that not all activities, outputs and outcomes can be monetised at this stage, this already compares very favourably with the £1.2 billion investment in the facility (which includes all capital expenditure and operational costs so far). Of this total, 86% comes from UK taxpayers, **with around £1 billion in investment from the Government via UKRI's STFC.**

The study developed 28 **case-studies** from the plastic degrading enzyme to the new synthetic vaccine against the Foot-and-Mouth disease virus, which are presented in Appendix A and cover academic and industrial use of Diamond, as well as suppliers of the facility. These case studies were selected on the basis that they showed most potential (based on existing material and survey responses) for quantifiable economic impact and, through further desk research and interviews, the study team attempted to obtain quantified information on impacts and come to a monetisable value in each case. The study hit issues, however, with the willingness or ability of those consulted to quantify impacts or attribute some part of these to Diamond. In addition, users were wary of sharing information relating to business and financial improvements, for reasons of commercial confidentiality. Some were even concerned about publicising their use of Diamond to competitors. Several cases were taken a little further, allowing the study to present selected examples of (potential, monetised) commercial benefits, but these are insufficient to generalise from.

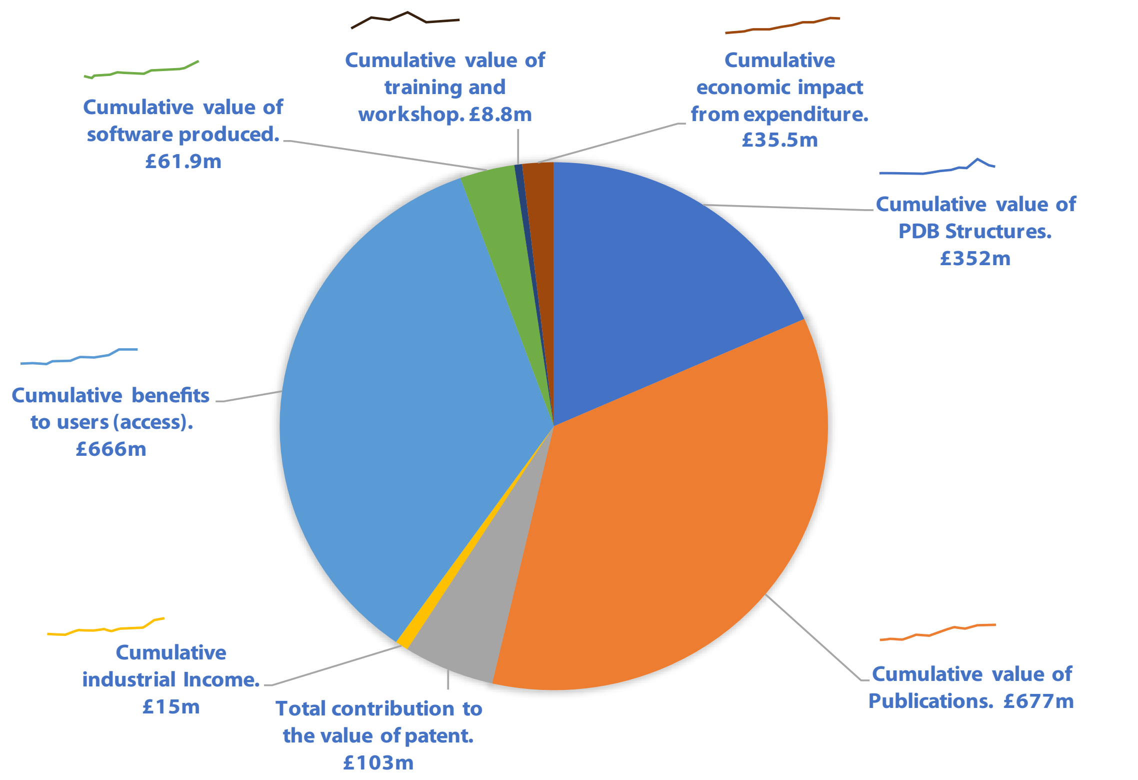


Figure 21: Break down of impact areas mapped as part of this report with trend data (where available) showing the steady growth over time.

In addition, **Diamond has wider societal benefits** that it has not been possible to monetise. These include:

- **80,000 visitors reached** so far through a programme of engagement at the heart of the facility supporting the UK Skills' agenda in science, technology, engineering and mathematics (STEM).
- Some of **the most challenging scientific questions** being investigated by **its 14,000-strong user community,** with **a part to play in 21st century challenges**, from new technologies and environmental remediation to health and well-being.
- Widespread awareness of the value and relevance of STEM subjects to our everyday lives through many news articles and outreach activities.

It was possible to monetise some of the benefits, however this estimate of total economic impact is only a sample of the overall benefits:

- Since the beginning of operation in 2007, Diamond has been involved in the publication of over 9,600 articles**,** resulting in a cumulative impact so far of £677 million in terms of the **production of research output** – based on the opportunity cost of time spent on developing publications based on data collected on the facility's instruments and assuming that the wage of researchers reflects the values of their time to society (but not including the value of the advances and innovations that these peer reviewed publications may then underpin).
- £551.5 million in **direct benefits to individual users** each year through access to beamtime and support – which has been inferred from the fees that users are willing to pay for time and services provided via the proprietary access route to beamtime at Diamond (a technique called 'stated preferences'). This figure represents the average between lower- and upper-bound estimates, where the lower bound is based on the minimal fee paid by proprietary users, while the upper bound is based on a higher range fee (but benchmarked against other similar facilities).
- £352 million in value through Diamond's contributions to **structures deposited** in the world's **Protein Data Bank** (PDB) – based on an economic analysis of the likely costs to replicate the archive in 2016 and Diamond's proportional contribution to this archive. Diamond contributed one-fifth of the total generated by all European synchrotrons over the period studied. Please note that only 45% of the structures solved at Diamond have been monetised.

- Patents citing Diamond publications are collectively valued at £10.2 billlion (in 2018 prices). The exact criticality of Diamond in each case is unknown – but some proportion of this considerable sum can be 'claimed' by Diamond. A conservative estimate of this proportion is around 1%, which would mean that **the contribution from Diamond could be worth at least £103 million.**
- An estimated £51.3 million valuation for the **software and applications** produced at Diamond**.**
- £35.5 million in net economic impact to the UK since 2007, generated from Diamond's operational expenditure. This is based on the contribution to the UK economy through direct impact arising from paying salaries to Diamond employees, induced impact on UK economic activity generated by these employees spending their incomes, and indirect impact on economic activity through Diamond's purchase of goods and services from UK suppliers. In line with Greenbook guidance, this figure also accounts for leakage (benefits flowing outside the UK) and deadweight (expenditure that would have happened anyway). It is also worth noting that previous impact studies (e.g. of ISIS) included the total *gross* economic impact to the UK, which have not been used here (but would equate to over £80 million each year for Diamond).
- £8.8 million in **training** provided through Diamond (for free), based on **19,191 days** of training across **7,668 attendees** in the past five years and the commercial rates paid for similar courses. Please note that data beyond the past five years was not accessible for this study and therefore the actual value of the training provided is very much underestimated here. The complete impact of those training days is impossible to quantify, therefore we had to resort to estimating the commercial value instead based on willingness to pay for similar training.
- £15 million in industrial income since the start of operations.

There are also **other benefits that were monetised** through the study, but based on fewer datapoints, meaning that we have less confidence in extrapolating accurately to wider populations. These benefits have therefore not been incorporated into the cumulative impact figure above. They do however provide useful indications of the scale of likely impact in these other areas. They include:

- Up to £50.5 million in net direct benefit to Diamond's suppliers each year – based on estimates of additional turnover generated as a result of being a supplier to the facility, but excluding the value of any contracts awarded by Diamond itself (i.e. capturing the additional sales to other organisations, based on new or improved products, improved reputation or other benefits realised through Diamond). This is extrapolated from 5 suppliers who on average reported that each £1 of contracts had led to an additional £2.40 in additional sales to other organisations.
- £0.7 million in contributions to the value of patents created each year by proprietary users of Diamond – this is an estimate, based on an estimated 75 patents that have been or will be submitted by past proprietary users. This is extrapolated from 24 respondents, of which 50% indicated that they have or will submit a patent based on their research at Diamond. Using the results of the survey of UK inventors mentioned above, we have placed an estimated value on these patents and then only assumed that 1% of that value is attributable to Diamond.
- Diamond has also been playing a **major role in the scientific response to the Covid-19 pandemic**, working on the design therapies from brand-new drugs and the repurposing of existing drugs. It has also made scientific contributions to the understanding of how the SAR-CoV-2 virus works at the atomic and molecular level, thereby helping better design a range of diagnostics and other therapies.

3. Overview

3.1. Inputs

Inputs	Key indicators	Sources of evidence
Investment	• Value of investments made by BEIS/STFC, the Wellcome Trust and Others for a total amount of £1.2 billion • **762 FTE staff**	Diamond finance Diamond HR database

3.2. Activities

	Activities	Key indicators	Sources of evidence
Scientific	Development of facilities	• **32 Beamlines** • **11 electron microscopes**	Diamond KPIs
Scientific	Use of facilities by users	• **14,274 experimental shifts** delivered in 2019/20 for academic users which illustrates the current level of activity; this is almost a 9-fold increase since 2007 • **5,851 remote user visits** and 6,454 onside remote visits in 2019/20. Overall user visits have increased by a factor 17 since 2007	Diamond KPIs
Scientific	Use of facilities by users	• **700 user visits** via the proprietary access route **180 companies** using Diamond for their research since 2007	Diamond contractual information
Scientific	Collaborative activities and ventures	• Diamond has **68 active formal scientific collaborations**; **22 new collaborations** are being progressed as we issue this report • In addition, Diamond has **54 active grants**, **25 new grants** having been awarded in 2019/20	Diamond
Technological	Industrial R&D	• **180 companies** have been using Diamond for their research & development since the start of operation	Diamond contractual information
Technological	Internal R&D	• **200 staff** who are continuously working on the improvement of the machine and instruments	Diamond HR data
Technological	Supplier based innovation	• Diamond has issued non-construction contracts worth over £210 million between 2007 and 2019. Due to the high technical specifications of Diamond's facilities, very high-quality instruments are often required and commissioned. This entails a great deal of collaboration, mutual testing and feedback as products are developed	Diamond procurement data
Technological	Computing and Software Engineering	• **80 software related roles** employed at Diamond as of August 2020, with an estimated **670,000 hours of development** work undertaken by Diamond employees since 2010	Diamond HR data and Diamond desk-based assessment

	Activities	Key indicators	Sources of evidence
Societal	Public engagement	• **6,000 visitors** in 2018/19 alone and a cumulative number of around 80,000 visitors since start of operation • **Open days** for the public and schools • **Talks and webinars** for schools • **School work experience/summer placements** • Other visits and events	Diamond event log
Societal	Training and workshops	• Doctoral Training Centre visits • Beamline training • Conferences • Summer schools • Synchrotron radiation users' meetings • Teacher training • Software training • Collaborative Computational Project visits • Data processing training • University student visits • Sector specific workshops/symposiums • **181 training events** between 2013 and 2020	Diamond event team and event log
Societal	Students en-gagement	• Minimum of **2 Advanced Engineering Apprentices** recruited per year • Programme to encourage staff to enter internal apprenticeship • **12 students** every year undertake a year in industry placement with **46 students** hosted since 2016 • **62 students** since 2016 have undertaken summer placements	Desk research
Societal	Press and media activities	• Diamond has published over **440 news articles and 415 science highlights,** as well as around **100 featured articles** on its website since 2006 • Programme of engagement with press based on the activities delivered by the facility • Media training for staff & users	Diamond website
Economic	Purchase of supplies	• **9,000 contracts** are placed by Diamond each year, with a total value of **~£40 million** • Currently, there are **434 suppliers** on the procurement database • Diamond has issued non-construction contracts worth over £210 **million**	Diamond contracts database
Economic	Employment	• Diamond employs over **750 staff**, the majority of whom are scientists, technicians, engineers, and professional staff, this represents an investment of around £44.8 million per year (2019/20)	Diamond HR and finance

3.3. Outputs

	Output	Key indicators	Sources of evidence
Scientific	Knowledge creation	• **9,600 articles** published in peer reviewed journal as of September 2020 • **Almost 77% of the articles in the Diamond publications database are open access (according to data from SciVal 2010-2019, all types of open access included). 9,960 structures** deposited in the PDB • In 2018, **34% of all structures solved by synchrotrons in Europe** and around **13% of all worldwide** synchrotron structures were solved at Diamond	Diamond KPIs
Technological	Industrial R&D	• **15%** of 303 academic user surveyed reported that their research using Diamond had already led to one or more **innovation-related outputs including** new patent applications (**5%**) • **1 in 10 Diamond** publications has been cited by a patent (**941**) with a total patent citation count of **3,455** • At least **2 start-ups** have resulted directly from Diamond research	Technopolis survey of academic users Lens.org (patent database)

Technological	Internal R&D	• More than **1,000 publications** in the Diamond publications database are related to technical developments
		• There are more than 100 licences arising out of Diamond collaborative research. For example:
		    • Development of CombiPuck
		    • Development of F-switch
		    • Development of read-out ASICs
		• The technological requirements of Diamond have also resulted in **spin-off** companies such as Quantum Detectors
			Desk research

Technological	Supplier based innovation	• 62 suppliers replying to our survey reported several specific innovation related outputs resulting from their work with Diamond:
		    • **2 new licence agreements**
		    • **13 new products and services**
		    • **7 new processes**
		    • **1 new start up**
			Technopolis survey of suppliers

Technological	Computing and Software Engineering	• **Dozens** of scientific applications including **GDA** and **DAWN** • **Dozens** of technical applications and code for **hundreds of industrial controllers** • Several data administration programmes and systems such as the Diamond UAS and ISPyB	Desk research

	Output	Key indicators	Sources of evidence
Societal	Public engagement outputs	• **236 events** between 2014 and 2019 • **51,170 interactions** with the public between 2014 and 2019 (Teachers, Primary, Secondary, Sixth form, Adult, Family)	Desk research
Societal	Training and workshops	• **7,668 attendees** who received **19,191 days of training** collectively	Desk research
Societal	Students engagement	• **149 Diamond funded students** who have successfully completed their PhD studentships and currently there are 97 current active PhD studentships at Diamond • **Around 20% of the Diamond user community** (14,000 registered users) is categorised as a student or an early career researcher in the user database. This demonstrates the wider impact on skills	Desk research
Societal	Press and media activities	• Diamond itself was featured **444 times online across 32 countries** within the past year (2018/19) • **136 items** relating to Diamond in UK broadcast media (2018/19) • There have been **6,494 news** stories about Diamond publications by **1,061 unique news** outlets in **64 countries** (source Altmetric) • Altmetric reports **83,732 mentions for 8,085 Diamond publications** indexed by Altmetric • **8% of Diamond publications** are in the **top 5%** of all research outputs scored by Altmetric	Desk research Altmetric
Economic		• Start-ups (already identified above) • Spin-off (already identified above) • New products and services being developed • Licences for Diamond and its suppliers • Contribution to the development of the Harwell campus and area with new centres and businesses	Desk research Technopolis survey of suppliers

3.4. Outcomes

	Outcomes	Key indicators	Sources of evidence
Scientific	Knowledge creation	• Important scientific advances reported by the majority of academic users surveyed	Technopolis survey of academic users
Scientific	Outcomes for facility users	• 94% of 321 academic users surveyed claimed that their use of Diamond had been **beneficial for their national or international reputation** • Evidence from the user survey that Diamond is playing a role in **academic recognition** (see Appendix F) • 54% of 318 academic users surveyed reported that their use of Diamond had been **very important or critical** to their subsequent ability to **access grant funding** • Evidence from the user survey that using Diamond had led to improvements in the users own **knowledge, skills and capabilities**	Technopolis survey of academic users
Scientific	Outcome for Industry users	• Evidence from the industry user survey that using Diamond had led to improvements in the **skills and capabilities of staff** • 73% of 22 industry users surveyed stated that Diamond was **very important or critical** to their part of their business	Technopolis survey of industry users
Scientific	Outcome for Diamond	• Improved scientific capabilities & achievements in the UK • Consolidation of the reputation of UK science • Increase in the capacity of the science community • Maximising of benefits for research institutes working together • Increase in attractiveness for Industrial clients (demonstrated by growth of industry usage) • New collaboration opportunities	Desk research

	Outcomes	Key indicators	Sources of evidence

Technological	Industrial R&D	• There is evidence (limited) that Industry users use of Diamond has had benefits in:
		  • **Increase turnover**
		  • **Employments**
		  • **Costs saving**
		• Increased efficiency and productivity of industrial partners
			Technopolis survey of industry users

Technological	Internal R&D	• Ability to deliver world leading instruments and support to the user base as demonstrated by science impact and bibliometric analysis	Desk research
Technological	Supplier based innovation	• Suppliers having reported reputational benefits to their work with Diamond • Increased efficiency and productivity of supplier base	Technopolis survey of suppliers
Technological	Computing and Software Engineering	• 90% of 321 academic users surveyed rate the facility and equipment (including software) as **good or excellent** • Software developed at Diamond is now used at other facilities • Ability to **support the science** undertaken at Diamond and handle the **20PB** of data recorded to date	Desk research
Societal	Public engagement outputs	• There is evidence that Diamond has helped student visitors in several ways especially in **informing decisions** on further **education** and their **choice of career** • Most interactions recorded by Diamond can be classified as **mid-level interactions** lasting around 2 hours • Advocacy for STEM careers • Increased **interest** in the **value of science** for **society**	Student survey (Diamond) Desk research
Societal	Training and workshops activities outcome & student engagement outcome	• Furthering of STEM skills • Encourage long-term careers in STEM • Development of staff delivering mentoring, training and support	Student feedback presentation Number successful PhDs Number successful Year-in-Industry projects Number of supervisors
Societal	Press and media outcome	• Awareness of new research addressing global challenges and the UK's societal needs	Desk research

Economic	Global	• **Synergy with the UK's Government policy**
		  • Delivering knowledge generation for the **clean growth agenda**
		  • Experiments that deliver **big data**
		  • Science **helping an ageing society**
		• **Enhancing the UK skills base**
		• 92% of 302 academic users surveyed indicated that the existence of Diamond was **very important / critical for the attractiveness of the UK as a place to conduct research** (i.e. as a means to attract / retain talent)
		• Contributions to improving UK economic performance through industrial and academic R&D
			Technopolis survey of academic users

3.5. Impacts

	Impact	Key indicators	Sources of evidence
Scientific	Knowledge creation	• Based on study done in 2017, Diamond's contribution to the PDB (4,666 structures deposited) can be valued at £352 million. Please note that only 45% of the structures deposited by Diamond have been monetised. • Since the beginning of operation in 2007, Diamond has been involved in the publication of over 9,600 articles which have a total estimated value of £677 million • The **impact of journals** in which Diamond publications appear is high (**65% above average**) • The **impact** of the publications themselves is **59% above the world average** • In fact, **19%** of Diamond publications belonged to the **top 10% most highly cited in their field** • Patents citing Diamond publications are collectively valued at £10.2 billlion (in 2018 prices). A conservative estimate of this proportion is around 1%,which would mean that **the contribution from Diamond could be worth at least £103 million.**	PDB Diamond publications database CTWS and Scival Bibliometric report
Scientific	Industry income	• Diamond's annual proprietary income has grown, from £300 thousand (2008/9) to over £3 million (2019/20). Since 2008, the cumulative **income from industrial users** has reached over £15 million	Diamond Industrial Liaison Office
Scientific	Benefits to users	• Estimated direct benefits to users by providing free access to the instruments of £551.5 million (this is the average between lower and higher estimates)	Desk research
Technological	Industrial R&D	• 106 new product or services launched • 25 start-ups • 37 new licence agreements • 75 patents submitted	Technopolis surveys of academic and industry users
Technological	Internal R&D	• 50 licences • 1 spin-off	Desk research
Technological	Supplier impact	• There is some evidence that suppliers doing business with Diamond benefit from an increase in sales • 13 new products and services • 1 start-up • 2 new licences	Technopolis survey of suppliers
Technological	Computing and Software Engineering	• Estimated value for the software and applications produced at Diamond of £51.3 **million** (this is the average between lower and higher estimates)	Desk research
Societal	Public engagement impact	• Increased 'science capital' • Increased trust in the work of Diamond (and STEM in general) • Increased awareness of STEM careers and capabilities • Improved skills in students, staff and the public • Greater public awareness of UK Science and the benefits that it brings to society • Demonstrable accountability in the spending of public money	Desk research
Societal	Training workshops activities impact	• £8.8m **in training delivered in the past five years base on willingness to pay for similar training.**	Desk research
Societal	Student engagement impact	No methodology available for quantifying this area of impact.	
Societal	Press and media impact	No methodology available for quantifying this area of impact.	
Economic	Other economic impact	• Through its operational expenditure, Diamond has generated an estimated gross economic impact of £824 million and a total cumulative net economic impact of £35.5 million **with deadweight and leakage applied**	Technopolis analysis

The approach to the study comprised in-depth research of Diamond and its resulting impacts, using both primary and secondary data. The main methodological elements were as follows:

- Desk-based research to compile and analyse existing relevant data and evidence
- A programme of 36 stakeholder interviews to capture views and perspectives from different groups
- Online questionnaire surveys of Diamond users (343 academic and 24 industrial/commercial responses)
- An online questionnaire survey of Diamond's past suppliers (62 organisations responded)
- The development of 28 user and supplier case studies (based on desk research and 30 interviews)
- A desk analysis to profile key benefits and impacts
- Desk assessments carried out by the Diamond team to map activities, outputs, outcomes and impacts to complement the work undertaken by Technopolis

This report is complemented by a set of appendices, which sets out the key elements from the Technopolis study.

3.6. Diamond's facilities and capabilities

Diamond is the UK's national synchrotron facility. Since becoming operational in 2007, it has been a leading **centre for synchrotron science** on the world stage, supporting UK universities, institutes and companies to undertake research in a diverse set of areas and sectors. It employs scientists, engineers, technicians, and professional staff who provide support and services to its users, undertake R&D and engage in a range of other training and public outreach activities. Diamond is a not-for-profit company, funded by Government through one of the research councils under UK Research and Innovation (UKRI) called the Science and Technology Facilities Council (STFC), in partnership with the Wellcome Trust – respectively owning 86% and 14% of its shares.

At the heart of Diamond sits a machine called a **synchrotron**, half a kilometre in circumference. Magnetic and electric fields are used to accelerate electrons to almost the speed of light, producing intense beams of X-rays, infrared and ultraviolet light. These beams are particularly useful for the detailed study of atomic and molecular structures. Synchrotron light is also emitted in pulses of less than a nanosecond, enabling their use in studying ultra-fast reactions. The light is channelled out of the synchrotron machine called a storage ring and into the experimental stations called **beamlines**, of which there are now 32 in operation and the 33rd coming online by late 2020.

Beamlines and instruments are organised into science groups:

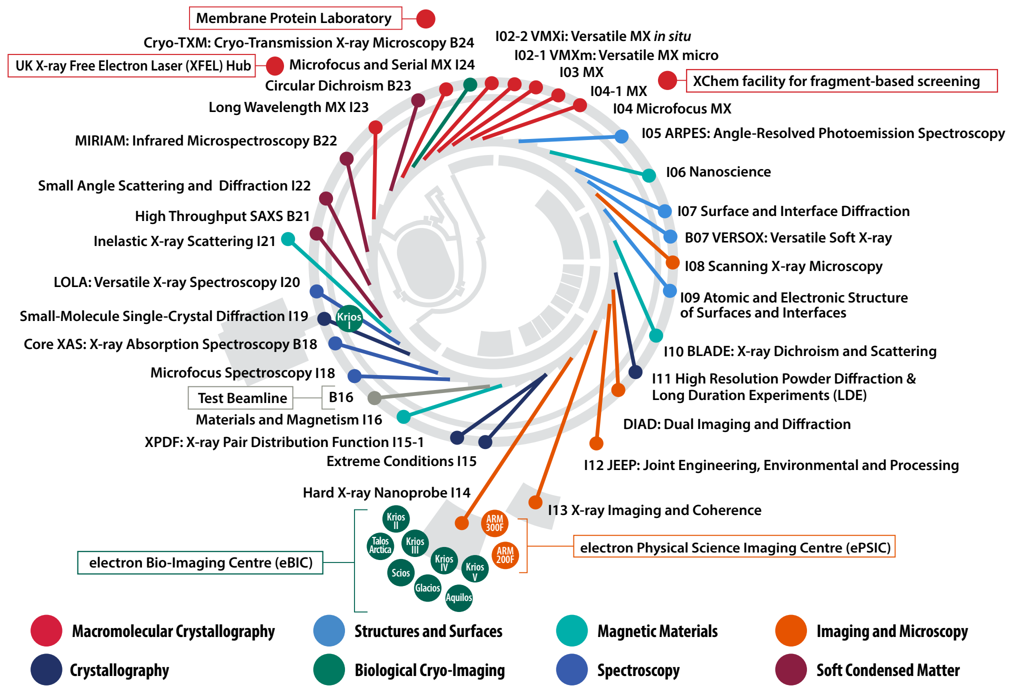


Figure 3-1: Instruments and Beamlines on offer at Diamond (2020)

3.7. The size of the investment

The investment for Diamond, initiated over the three phases of capital allocation over a period of 17 years, has totalled £493 million[1] (£264.1 million for Phase I, £124 million for Phase II and £105.6 million for Phase III). Diamond's **annual expenditure** (including both operational and capital costs) started in 2007, grew in line with the development of the facility and has now reached around £85 million[2]. The overall cost of Diamond, comprising the capital investment and operational cost from the creation of the organisation until today is around £1.2 **billion**.

The UK government contributes 86% via STFC as part of UKRI, while Wellcome contributes 14%.

By dividing the cost supported by the UK government by the number of taxpayers, we can deduce the cost of Diamond per taxpayer for each financial year. It averages around **£2.05 per year for the period 2009-2019 and has stabilised around £2.35 in the past few years**.

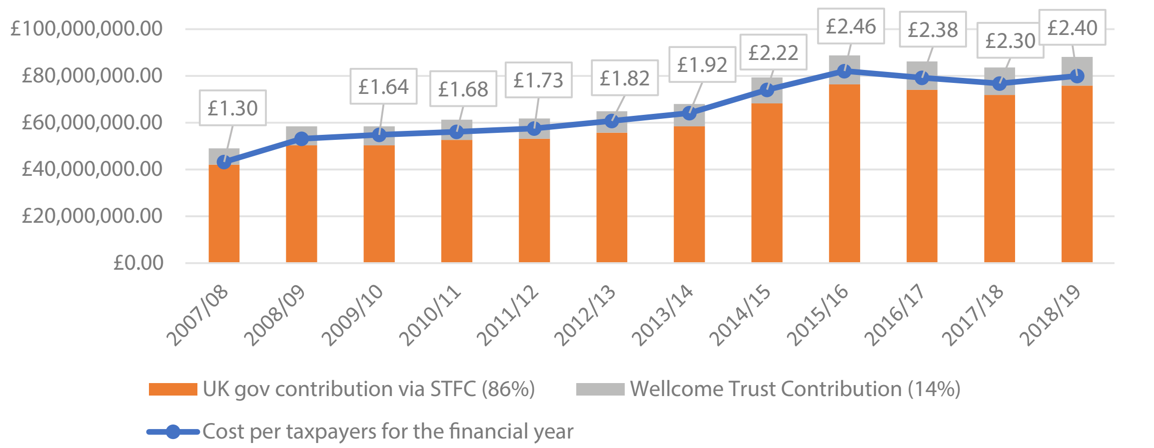


Figure 3-2: Cost per taxpayer for the period 2007-2019. The number of taxpayers for 2008/9 is not available from the .gov website, so an average between 2007/8 and 2009/10 was used.

1 Financial reporting up to 2014/15 did not include VAT, later reports do include VAT this may explain the difference from other reports.

2 The complete financial table is given in Appendix F.

Due to Diamond's ownership model, it has widely benefited from full autonomy in terms of **procurement** processes. Its procurement system is supported by a small team who enable direct contact with science and technical staff, to enhance understanding of the many complex elements that are being purchased. On average, around 9,000 orders are processed electronically per year by Diamond, with a total value of ~£40 million. Around two-thirds of Diamond's suppliers are UK-based, and they account for just over two-thirds of all expenditure.

Diamond also employs over 750 staff, which includes in-house scientists, engineers and technicians (in addition to various management and support staff). Given the highly technical requirements of the facility, the majority of employees are scientists, technicians and engineers (see table below). The facility also requires a large IT team to offer support for the collection, processing and analysis of the experiment outputs.

Position	Headcount	FTE	% of total FTE
Engineers (Engineer and Senior Engineers)	125	122	16%
Technician	124	123	16%
Information Technology	117	116	15%
Post-Doctoral and Students	65	65	8%
Professional Senior Management and Other Professional	84	82	11%
Scientist, Senior Scientist and Science Senior Manager	189	187	25%
Support, Admin and Other General	69	67	9%
Total	**773**	**762**	

Figure 33: Summary of staff profiles at Diamond. Source: Diamond, Human Resources data at end of September 2020.

The strength of computing capabilities and expertise available at Diamond is also key to the functionality and usability of the machine, the beamlines and the data measurements generated. In the technology section of this report, the substantial contribution made by groups working on computing is captured. As part the study, interviewees regularly highlighted that the analysis and interpretation of data is one of the more challenging parts of experimental work, and so the software tools, training and expertise provided by Diamond are a very important part of the facility's offering. The ever-rising volume and complexity of data will only increase the criticality of these capabilities and a methodology for monetising impact is provided later in the report.

4. Model

4.1. Glossary of terms

Objectives: The strategic goals of the organisation.

Inputs: The raw resources that provide a basis for delivering the programme of activities. Inputs can include money, technical expertise, relationships and personnel.

Activities: The actions of Diamond staff, collaborators, and users.

Outputs: The tangible and intangible products that result from the activities.

Outcome: The benefits that are resulting from the delivered activities.

Impact: The deduced value of the outputs and outcomes, whenever possible the value is monetised.

4.2. Recommendation for future assessments

Based on the experience and learning from this study, Technopolis has put forward a proposal for an **evaluation framework** that could be used as the basis for tracking performance in future. This is a revised and updated version of the framework deployed for the current study and is intended to support future evaluations by ensuring there is a more wide-ranging and complete record of achievements across each of principal impact pathways.

The framework is designed to allow a high degree of quantification across all impact pathways, including **monetisation of benefits**, where possible. The current study explored several options and techniques to monetise impact, some of which experienced difficulties and limitations. These methods and the lessons learned have been documented to inform future evaluation efforts.

The framework includes a series of **suggested metrics**, designed to allow the facility to more clearly understand and demonstrate the extent to which it is supporting beneficial outcomes. Most of the evidence relating to inputs and outputs could be derived from Diamond itself, via established databases and reporting, while the evidence for computing outcomes and impacts could comprise a mix of internal (Diamond) and external (future evaluators) data collection exercises.

Some of the suggested sources of evidence already exist, while others are new, and the report sets out recommendations for **improvements, extensions and additions** to monitoring and evaluation activities to help address any gaps and strengthen the findings. This includes additional questions within beam time application and user surveys, a more-standardised biennial bibliometric exercise, additional social-/media analysis, and an increase in the numbers of case studies developed. Future evaluation exercises should also dedicate more resource to engagement with proprietary users and suppliers, so as to ensure a larger number of inputs (and datapoints) can be obtained, as well as to help in the quantification and monetisation of benefits through individual case studies.

The framework also points to the need for several **new data collection activities**, including suggestions for new (periodical) surveys (e.g. of Diamond-related start-ups and suppliers, as well as unsuccessful applicants for beamtime), a follow-up survey with past users and new questionnaires to collect feedback from attendees of Diamond's various training and public outreach activities.

5. Diamond's objectives

Diamond's objectives are stated in the 10-year vision strategy document that was published by Diamond in 2015[3].

The objectives are:

1. **To deliver internationally leading synchrotron research and innovation**
   - Provide a highly reliable, high performance source of X-rays, ultraviolet and infrared light
   - Offer world leading beamlines and analytical tools
   - Provide exemplary technical and scientific support for experiments
   - Administer world leading data handling and analysis
   - Recruit and retain the best talent
   - Maintain world leading technology to underpin our science delivery
2. **To maximise the scientific, economic and societal impact of Diamond**
   - Attract and support the very best research groups in universities and institutes
   - Drive even stronger engagement and support for UK industry
   - Work in partnership with other organisations to help realise the full potential of the Harwell Campus
   - Build stronger collaborations at European and International levels
   - Ensure the widest possible dissemination of Diamond's scientific output
3. **To ensure the long-term sustainability of Diamond as a national facility**
   - Deliver value for money in all aspects of our operations
   - Engage effectively with stakeholders at all levels
   - Identify and access new income streams
   - Maintain an operational infrastructure that is efficient and resilient
   - Ensure governance is fully transparent
   - Maintain health and safety at the forefront of operations
4. **To engage and inspire the general public through promoting science**
   - Strengthen educational activities for students at all levels
   - Put public engagement and communications at the heart of the facility
   - Champion the importance of STEM skills at all levels
   - Increase exploitation of opportunities to disseminate science at a global level
   - Ensure there is effective two-way communication at all levels of the organisation
5. **To continuously plan for Diamond's technical and scientific future**
   - Ensure there is a clear planning cycle for delivery of activities
   - Adapt the operating model to changing requirements
   - Support the joint venture of the Harwell Campus

3 https://www.diamond.ac.uk/Home/Company/Vision-and-Strategy.html

6. Scientific impact

6.1. Scientific inputs

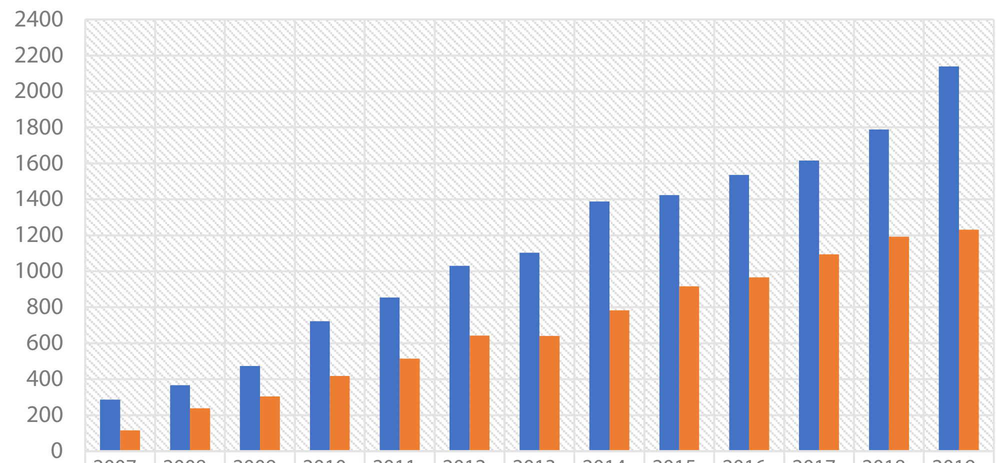
Diamond set out to deliver internationally leading synchrotron research and innovation. By the nature of this vision, measuring impact of its science is essential to the success of the facility.

The inputs that are enabling science can essentially be summarised as the monetary investment and the facility staff members.

The investment for Diamond was initiated over the three phases of capital allocation over a period of 17 years and has totalled £493m[4] (£264.1m for Phase I, £124m for Phase II and £105.6m for Phase III). Diamond's **annual expenditure** (including both operational and capital costs) started in 2007, grew in line with the development of the facility and has now reached around £85m[5]. The overall cost of Diamond, comprising the capital investment and operational cost from the creation of the organisation until today is around £1.2 **Billion**.

Diamond has recruited over **750 staff**, the majority of whom are in-house scientists, technicians and engineers.

Another input that can be considered are the proposals sent by the user community to use the instruments.



	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20
Proposals Submitted	287	367	473	723	855	1030	1104	1388	1424	1536	1615	1788	2138
Proposals Awarded	116	238	305	419	514	643	641	783	916	967	1095	1192	1232

Figure 6-1: Number of proposals submitted and awarded for peer reviewed access routes. Source: Diamond Annual Review

6.2. Scientific activities

Synchrotrons are one of the most important types of research facility for imaging and non-destructive testing of materials and structures, as well as for the acceleration of drug discovery and development. The research that they enable is often not achievable by other means. For instance, beamline I04-1 allows for routine medium-throughput fragment screening by crystal structure, which was a world first when it opened in 2015. Synchrotrons also provide unique knowledge for a **wide variety of fields and sectors** and are unusual in both the breadth of R&D that they support and the range of academic and industrial users that they attract. Diamond is therefore a critical piece of national infrastructure.

As part of its strategy, Diamond has secured **a range of integrated facilities,** which were initially funded through strategic grants to allow scientists access to a range of associated complementary facilities, from sample preparation laboratories, equipment, and services to new expertise. These include the UK Life Sciences XFEL hub, where samples and technology are developed to utilise complementary techniques offered by Free Electron Lasers (FELs) across the world, the fragment screening laboratory, and the Membrane Protein Laboratory to a name a few.

The electron Bio-Imaging Centre (eBIC), which provides scientists with cryo-electron microscopy (cryo-EM) expertise and equipment is one of the largest such investments. Recent advances in cryo-EM have enabled high-resolution biomolecular images that are vital for understanding disease and developing more effective drugs and vaccines. The recent investment in eBIC has transformed access to this innovative technology for the UK life sciences sector, enabling it to continue to be at the forefront of structural biology in drug discovery for both academia and industry. eBIC was established at Diamond following the award of a £15.6 million grant from the Wellcome Trust, the Medical Research Council (MRC) and the Biotechnology and Biological Sciences Research Council (BBSRC). The location of eBIC enables scientists to combine their techniques with many of the other cutting-edge approaches that Diamond offers; whilst a partnership with the University of Oxford allows users to access the Polara, a high-containment cryo-electron microscope.

Another integrated facility is the electron Physical Science Imaging Centre (ePSIC), a collaboration between Johnson Matthey (JM), Oxford University and Diamond that provides expertise and equipment for the study of electron microscopy and materials characterisation. JM made a multi-million-pound investment with the purchase of an atomic resolution electron microscope. On its launch, ePSIC was announced by the company as a "world-class centre for the study of nanoscale materials", providing "unrivalled facilities for research across the physical sciences in the UK". ePSIC gathers two state-of-the-art electron microscopes for the physical sciences designed to provide scientists with atomic level images in a range of technologically important materials. Embedded at a synchrotron to support biology and physical sciences, ePSIC and eBIC create one of the largest microscopy capabilities in the world.

Diamond is also engaged in a significant number of collaborative ventures. Diamond has **68 active formal scientific collaborations**; **22 new collaborations** are being progressed as we issue this report. In addition, Diamond has **54 active grants**, **25 new grants** having been awarded in 2019/20.

Diamond's co-location next to existing UK national world-leading laboratories like the **ISIS Neutron and Muon Source (ISIS)**, **Central Laser Facility (CLF)** and others onsite have brought scientific synergy to the research activities.

ISIS is a world-leading centre for research operated by STFC on the Harwell Campus. Neutron and muon instruments give unique insights into the properties of materials on the atomic scale and thereby offer a range of complementary techniques to what Diamond has on offer. Over 200 papers have been published using one of the two facilities.

CLF is one of the world's leading laser facilities, providing scientists from the UK and Europe with an unparalleled range of state-of-the-art laser technology. It provides a broad spectrum of laser facilities, from high intensity laser systems to ultra-fast sources and laser microscopy techniques and thereby offer a range of complementary techniques to what Diamond has on offer.

Diamond has also played a key role in the co-location of other activities to the Harwell campus, such as:

The Research Complex at Harwell (RC@H) is a science-led national resource with a mission to enable and add value to outstanding new science that benefits, and benefits from, the UK's Central Facilities. Diamond holds 10% of shares in RC@H as it underpins core areas of research. For example, RC@H houses Diamond's sample preparation laboratory for life sciences research (alongside other capabilities).

RC@H has a mix of research hubs, individual groups and facilities that fall within the physical, life and laser sciences. Amongst many others, it houses the UK Catalysis Hub which is funded by the Engineering and Physical Sciences Research Council (EPSRC) - a national network of 35 collaborating universities – where programme teams are offered access to Diamond through allocated experimental shifts. Catalysis

4 Financial reporting up to 2014/15 did not include VAT, later reports do include VAT this may explain the difference from other reports.
5 The complete financial table is given in Appendix F

lies at the heart of the chemicals industry that represents a £50 billion sector in the UK economy, but the research will also feed into other areas, such as the more effective use of water and energy, waste minimisation, material reuse and reduction in gaseous emissions.

The **£80 million Faraday Institution**, the UK centre for electrochemical energy storage science and technology, and research arm of the Industrial Strategy Faraday Battery Challenge and the £100 **million Rosalind Franklin Institute**, a national centre for interdisciplinary life sciences research. Both were located here in part because of the opportunities for collaboration with Diamond. Diamond was also reportedly a factor in choosing to locate the Structural Genomics Centre in Oxford. Stakeholders and users also suggested that Diamond had encouraged the accumulation of expertise to the area more generally, with the facility considered an 'anchor tenant' for the Campus.

Manchester at Harwell. The University of Manchester first invested £4.6 million in the I13 imaging beamline which supports research across materials science, biomedicine, geology and engineering, and aims to be the most comprehensive and capable 3D X-ray imaging capability in the world. This investment was a springboard for Manchester to secure a long term presence on the Harwell Campus. To this end, Diamond welcomes 18 Manchester staff, including 2 science fellows who have been appointed in the following disciplines to foster better collaboration onsite: chemical and chemical engineering, catalysis, engineering and energetic materials and structures, energy storage and magnetism.

The University of Birmingham. Diamond and the University of Birmingham have been collaborating in developing the DIAD (Dual Imaging and Diffraction) beamline at Diamond since 1 April 2016 in order to combine expertise and promote and publish high-quality science in the UK. The key feature of the DIAD Beamline is that it will enable real time in situ characterisation of processes with concurrent imaging and diffraction measurements creating a unique offer in the world.

Harwell is now one of the largest research and innovation campuses in the UK, hosting 225 organisations, 6,000 people and £2 billion-worth of world-leading research infrastructure. It has been estimated to contribute £1 billion to the economy and, based on its success, has recently embarked upon a new ambitious expansion plan to create millions of additional square feet of working and research space.

As part of this socio-economic study, interviewees highlighted the importance of these various connections in exposing researchers to the possibilities of Diamond, helping to develop new markets where synchrotron science is not yet fully exploited.

Access to Diamond

Since the start of operations, Diamond has supported research at UK universities, institutes and companies, with some 14,000 users to-date. In 2019/20 alone, Diamond received 2,138 proposals for experiments on our instruments via peer reviewed access routes, requesting a total of 26,543 shifts. After peer review, 1,232 proposals were awarded beamtime. This resulted in 13,462 experimental shifts being awarded across 30 beamlines and 11 electron microscopes. Diamond welcomed 6,454 onsite user visits from academia across all instruments, with an additional 5,851 remote user visits and 700 industry visits through the proprietary route.

The two access routes - **peer-reviewed and proprietary** - offer users several access modes, from one-off on-site individual access through to full-service design, data collection and analysis.

As more instruments continue to come online at Diamond, the overall number of users and user visits per year will inevitably continue to expand further.

Non-proprietary (peer-reviewed) access to Diamond is free at the point of access, provided results are published in the public domain. This route is predominantly (but not exclusively) used by academia. Synchrotrons can support many experiments at the same time and therefore a high throughput of research. However, user demand is high, and beamlines are often oversubscribed by a factor of 2 or more.

The number of non-proprietary **user shifts delivered** by Diamond has increased **nearly nine-fold in the past 11 years**, while increased automation has meant more samples can be measured within a single shift. The research covers a diverse set of subject areas - predominantly physics, chemistry and biology/bio-materials, but also others (such as archaeology or food science).

As part of the Technopolis survey, a majority of academic users surveyed (87% of 345) reported that Diamond was very important or **critical for their research**. Most were also clear that, although there are often alternative sources and methods available, non-access to Diamond would have a range of negative implications for their research (e.g. increased costs and reductions in efficiency, quality and international competitiveness).

6.2.1. Academic activities (non-proprietary)

In 2019/20, 13,462 experimental shifts were awarded across 30 beamlines and 11 electron microscopes. Diamond welcomed 6,454 onsite user visits from academia across all instruments, with an additional 5,851 remote user visits.

It is difficult to quantify levels of **industrial access** via the non-proprietary route (above) because much of this takes place through academic institutions. However, analysis suggests that over a quarter (28%) of Diamond's academic users have collaborated or been sponsored by industry for work at the facility. Rolls-Royce, for example, has collaborated regularly with academic users at Diamond (in addition to its own proprietary work) to improve the performance and effectiveness of its products.

In a recent analysis (2014-2018) carried out for the League of Accelerator-based Photon Source (LEAPS), Diamond found that over 10,000 academic users[6] from more than 50 countries are exploiting the 33 beamlines and 11 electron microscopes that are now in operation at the facility. This emphasises the international nature of the facility and how widespread its activities have been.

6.2.2. Industrial activities (proprietary)

Diamond has worked hard to engage with industry. One of the critical elements of its success has been the establishment of Diamond's Industrial Science Committee (DISCo)[7]. Its creation and ongoing engagement in the shaping of the facility from the outset of the initial capital investment being made has had a positive impact on alignment of industrial expectations.

Since 2008, the number of industrial customers using Diamond for their research has grown to over **180 companies**[8]. The proportion of beamtime delivered through this route (3-7% each year) is higher than at many other facilities. This work is performed under contract guaranteeing confidentiality, with results only available to the customer. Since 2008 (when it began), over 180 companies have made use of Diamond via this route, including Rolls-Royce (aerospace), Hewlett Packard (electronics), Johnson Matthey (specialty chemicals), Infineum (automotive), GSK (pharmaceuticals) and Evotec (drug discovery). In 2019/20, over **700 industry visits** took place through the proprietary route.

Much industrial use of Diamond has historically been in the **life sciences**. This is partly due to the well-developed market in drug discovery/development, the speed and replicability of experiments and measurements possible, and the commonplace use of synchrotrons within the sector. Diamond's in-house capabilities and experience are also important, as is the support and investment of the Wellcome Trust and the recent opening of the eBIC (cryo-EM) facility, complemented by a multi-million pound investment by Thermo Fisher who have contributed two state of the art electron microscopes to work in partnership with Diamond to deliver cryo-EM services to the pharmaceutical sector. Innovations such as remote access, automation and robotics will have further supported life sciences work through higher volume, faster measurement. Interviewees suggested that Diamond's presence and capabilities in the life sciences are critical in anchoring many biomedical and pharmaceutical companies (and their R&D) within the UK.

6 Data from the user administration system submitted as part of a study carried out for LEAPS.
7 https://www.diamond.ac.uk/Home/Company/Management/DISCO.html
8 https://www.diamond.ac.uk/industry/Case-Studies.html

There is also a lot of potential in the **physical sciences**, where synchrotron light offers one of very few ways to look at material on an atomic scale. This ambition can be seen in the establishment of the ePSIC, as well through a strong physical science focus to future development plans. As technical capabilities evolve and market awareness grows, a wider range of companies in the 'materials space', as well as advanced engineering / manufacturing companies, are now being attracted to the facility. One key aspect is the increasing availability of *operando* or *in situ* experiments, where users can look at more complex systems that are closer to the 'real life' context – which is often invaluable for industrial users.

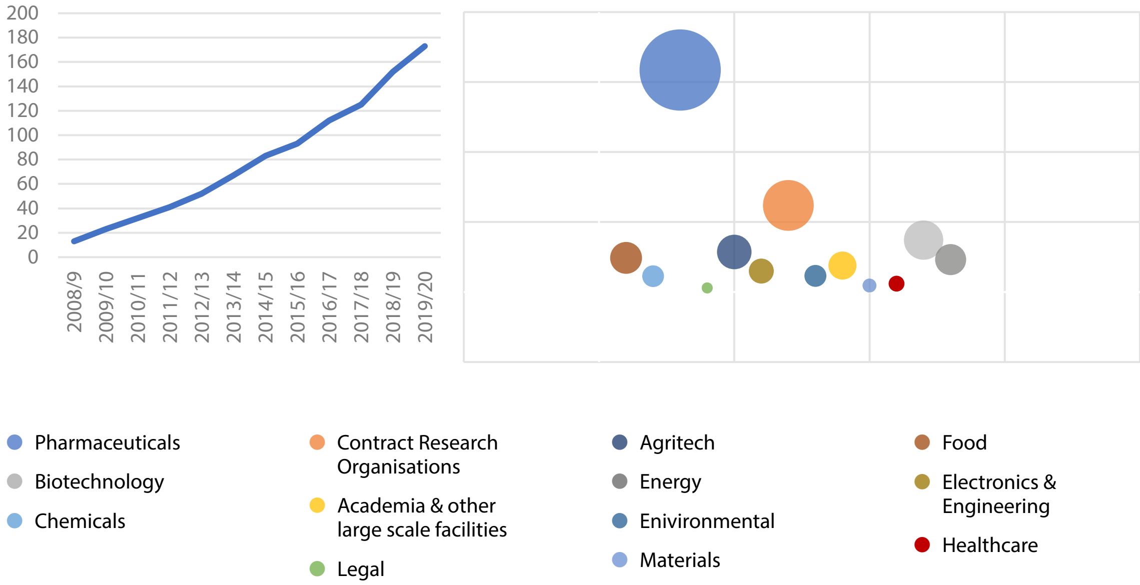


Figure 6-2: (left) Number of industrial organisations using Diamond via the industrial proprietary access route. (right) Graphical representation of the customer base using the industrial services at Diamond. Diamond Light Source Industrial Liaison Office.

6.2.3. Diamond's response to the COVID-19 pandemic

The many COVID-19 related research projects that Diamond is working on are a great demonstration of the powerful synergy between Diamond and its neighbouring research institutes, the Research Complex at Harwell and the Rosalind Franklin Institute. Diamond is working with its valued users and many partners to look at the fundamental interactions of the virus, from which it is hoped new therapies can be developed. It is also enabling the study of how existing drugs, that have already been tested and approved for other diseases, can be repurposed and used to treat patients. The array of specialised tools and instruments at Diamond, along with the scientific and technical expertise of its staff, allow for many different techniques to be used, from looking at the structure of the virus and fitting drugs into it, to taking direct images of the virus without its infectious material, making it possible to see how it interacts with drugs.

COVID-19 research at Diamond in 2020

Studying the viral infection in the native cellular context reveals that SARS-CoV-2 replication induces profound cytopathic effects in host cells

A research group led by Peijun Zhang, Professor of Structural Biology, Division of Structural Biology, University of Oxford, and Director of eBIC, Diamond Light Source, investigated SARS-CoV-2 replication under near-native conditions, exploiting a unique correlative imaging approach to depict the entire SARS-CoV-2 infected cell. Their results revealed at the whole cell level profound cytopathic effects of SARS-CoV-2 infection and have enabled modelling of SARS-CoV-2 genome replication, virus assembly and egress pathways. Understanding the multistage infection process is critically important as it bears the means of medical intervention to help combat COVID-19.

Structural Biology identifies new information to accelerate structure-based drug design against Covid-19

New research has identified potential ways forward to rapidly design improved and more potent compounds in the fight against COVID-19. The work is the result of a massive fragment screening effort to develop an antiviral targeting the SARS-CoV-2 main protease. The project was led by Martin Walsh, Deputy Director of Life Sciences at Diamond Light Source; Frank von Delft, Professor of Structural Chemical Biology at the University of Oxford and Principal Beamline Scientist of I04-1/XChem at Diamond; and Nir London, Assistant Professor at the Weizmann Institute of Science, Israel. The team combined mass spectrometry with the XChem facility at Diamond, to rapidly identify lead compounds for drug development to treat COVID-19.

Structural Biology reveals new target to neutralise COVID-19

Diamond, along with an international team of researchers, discovered a new and highly conserved site on the SARS-CoV-2 virus that can be neutralised by a specific antibody. Previous studies have reported that antibodies that block the virus interaction with the human receptor (ACE2) have a significant neutralising effect and can be used to save the lives of critically ill patients. However, this study published in Nature Structural and Molecular Biology describes a different target that can be bound in synergy with ACE2 blocking antibodies for a stronger neutralising effect. Together, with a group at a hospital in Taiwan, the team using the Electron Bio Imaging Centre (eBIC) at Diamond identified antibodies from a convalescent patient that could create a real potential for a drug target.

Engineered llama antibodies neutralise COVID-19 virus

A collaboration with researchers from Diamond Light Source, the Rosalind Franklin Institute, University of Oxford and Public Health England discovered that antibodies derived from llamas were shown to neutralise the SARS-CoV-2 virus in lab tests. They hope the antibodies – known as nanobodies due to their small size – could eventually be developed as a treatment for patients with severe COVID-19.

UK consortium launches COVID-19 Protein Portal to provide essential reagents for SARS-CoV-2 research

The Wellcome Trust and UKRI brought together leading centres of protein engineering and production including Diamond in an Open Science initiative enabling UK scientists to access protein reagents for critical research relating to SARS-CoV-2 free of charge.

COVID Moonshot

Diamond launched a call for Chemists to contribute to the fight against COVID-19. In collaboration with start-up company PostEra Inc. and an international group of scientists from academia and industry they teamed up to form this ground-breaking non-profit initiative. Their unprecedented aim is to develop a clinically effective antiviral more rapidly than ever before, by crowdsourcing designs of new inhibitors from chemists around the world who are mining the rich "fragment" data measured at Diamond in record time during March and April. All data will be released in real time and in the open to enable worldwide collaboration and rapid progress.

This collaboration has created a clear design-to-clinic strategy and timeline. Researchers can submit their designs to PostEra, who are running machine learning algorithms in the background to triage suggestions and generate synthesis plans to enable a rapid turnaround. Promising compounds will then be synthesised and tested for antiviral activity and toxicity.

Joint initiative announced to accelerate the search for COVID-19 drugs

Jointly with Exscientia and Scripps Research, Diamond in this new transatlantic partnership seeks to accelerate the path to clinical trials for potential COVID-19 antiviral treatments. Using Diamond's research on COVID-19 and research facilities, Exscientia will screen nearly every known approved and investigational drug - 15,000 clinical drug molecules - against COVID-19 drug targets to search for rapid treatments.

6.3. Scientific outputs

Diamond was established primarily for academic-led research, although, as we have seen, industrial use has increased over time, and so scientific publications are a key measure for the facility.

The scientific output of Diamond can essentially be summarised by the creation of knowledge which is indicated by the number of scientific articles published as well as the number of protein structures deposited in the worldwide Protein Data Bank (PDB).

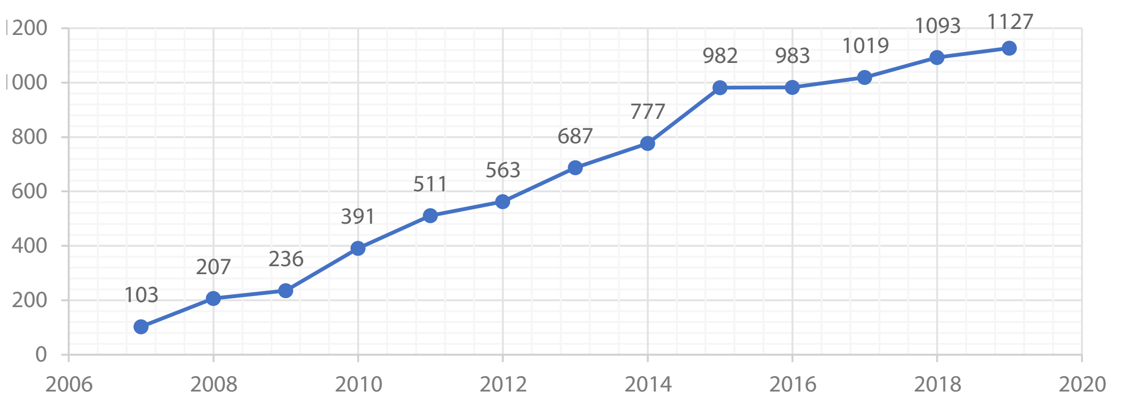


Figure 6-3 Number of articles published per year in peer reviewed journals citing Diamond's data or with at least one Diamond staff member as a co-author. Source: Diamond Publications Database

Scientists using Diamond's instruments and Diamond staff have published over **9,600 articles** in peer reviewed journals as of September 2020. This may be compared with the output of the previous UK synchrotron, the Synchrotron Radiation Source at Daresbury, which achieved 5,000 peer-review publications throughout its lifetime 1981-2008 with a total of 30 beamlines.[9]

9 https://stfc.ukri.org/files/dlcampusimpactstudy/

Additionally, the Diamond publications database also records 87 book chapters, 795 conference papers, 2 editors notes, 28 Magazine articles, 54 posters, 10 reports and 434 theses. All of these either using Diamond data or authored by Diamond staff. *(Please note that these other types of publications are harder to track and therefore the numbers are most likely very underestimated.)*

Synchrotrons have also increasingly been used to solve the **X-ray structures of proteins** (the three-dimensional arrangement of atoms in a molecule), thereby contributing to open-access databases such as the Protein Data Bank (PDB) – a global repository. These structures are the molecules of life found in all organisms and knowing their 3D structure is essential for understanding the molecule's function, providing insights in health and disease, food and energy production, and other topics. Diamond beamlines have been used to solve and deposit over **9,960 structures** into the PDB.

PDB data are freely and publicly available, without restrictions on usage, and the PDB archive is heavily used. For example, in 2017, more than 680 million structure data files were downloaded from the archive by PDB data consumers worldwide. An article describing the mission, vision and operations of the PDB is routinely used to cite the archive, and in 2014 it was ranked the 92nd most-cited research publication of all time, with PDB usage seen across 150 disciplines in applied and social sciences.

In 2018, 34% of all structures solved by synchrotrons in Europe were solved at Diamond and around 13% all worldwide synchrotron structures were solved at Diamond. To put those numbers in context, it is important to note that there are around 50 synchrotron light source facilities currently in operation worldwide[10]. It has to be noted that the pharmaceutical sector is estimated overall to be worth $1,250 billion per year[11], hence structural information will have impact on R&D performance of this sector.

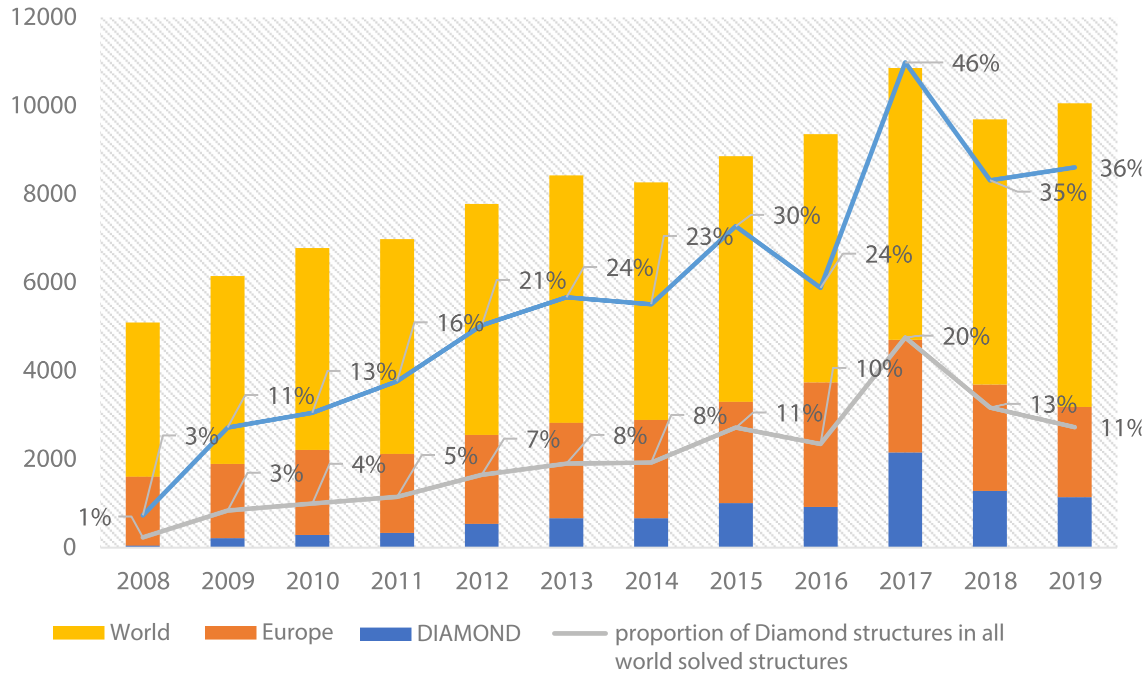


Figure 6-4: Protein structures solved at Diamond and deposited to the PDB and their relative proportions compared to European (upper line) and Worldwide (lower line) protein structures deposited

6.3.1. Academic

Diamond can provide a scientific view of the world not accessible through any other means and the majority of the ~300 academic users surveyed for this study could point to an important **scientific advance** that was attributable to their own use of Diamond. A selection of these examples were

10 https://lightsources.org/lightsources-of-the-world/

11 https://www.statista.com/topics/1764/global-pharmaceutical-industry/

explored further through case studies of academic users developed for this study. Some highlights are:

Professor John McGeehan (Portsmouth) using Diamond to better understand the function of a newly discovered bacterium, capable of digesting PET plastic through the production of an enzyme. Diamond allowed the team to solve the structure of the enzyme, opening the possibility of industrial applications.

Dr Bryan Charleston (Pirbright Institute) used Diamond to study why a synthetic foot and mouth disease vaccine falls apart. This served as the basis for £3 million funding from the Wellcome Trust and a Gates Foundation award to support further development towards a commercially viable vaccine. In September 2019, MSD Animal Health were granted an exclusive commercial licence for the vaccine.

Dr Joanna Collingwood (Warwick) used Diamond to understand the processes that lead to Alzheimer's disease, and in particular that atypical chemical reductions of iron in brains contribute to the pathogenesis of the disease. Trials of an iron-modifying drug are already underway as a result.

Professor Owen Addison (Birmingham) used Diamond to understand how materials in a defective implant were behaving with human tissue and significantly improved understanding of how implants behave. The research has fed into further research with industry on other metallic implants.

Dr Mahmoud Mostafavi (Bristol) undertook research at Diamond that validated models showing the expected 30-year lifetime of nuclear plants was overly-conservative. The study will be used as part of the evidence to the Office for Nuclear Regulation, demonstrating that a plant could continue operating.

Professor Kim Watson (Reading) worked with a technology firm to develop more thermally stable enzymes for use in the production of prebiotics. The research led to a novel enzyme being adopted by the company in the manufacture of their flagship product, which enabled higher yields, reduced downstream processing and produced less waste. Her group is now exploring its use in baby formula.

Professor Colin Pulham (Edinburgh) worked with a firm to determine the crystal structures of phase- change materials (PCMs); compounds that can store and release large amounts of heat through melting and solidification. This research helped determine the temperature at which different PCMs cease to function properly, enabling appropriate temperature cut-offs to be integrated in the firm's batteries.

Another example, highlighted by interviewees, was the work of Professor Edmonds (Nottingham) on **antiferromagnets**, which have the potential to make smaller, faster, more robust and more energy efficient data storage devices, possibly replacing all other forms of computing memory and transforming electronic devices. Assuming that there will be **new IP and start-ups** linked with UK research, future sales (turnover, royalties, shares) are likely to run into **the tens of millions of pounds**, given the **critical role** these technologies could play in this large and **rapidly growing market globally**.

6.3.2. Industrial

As part of the Technopolis survey, three-quarters of industry user respondents (73% of 22) stated that Diamond was very important or critical to their part of their business, and nearly all (95%) expect to use Diamond again.

A selection of quotes, highlighting the value of Diamond to these businesses is shown below:

> *The equipment, beamlines and computation at Diamond are the best in the world, providing the best answer for our needs and delivering results exactly when we need them. For the last 10 years, Diamond has been an essential extension of our lab, allowing us to remain at the top of a very competitive market.*
> *(Pharma research company)*

> *Diamond is an essential part of the R&D jigsaw puzzle. It provides real-time data and high-quality light, without which our research would take place at a much slower pace, or not at all.*
> *(Energy and materials company)*

> *It has very high-resolution microscopes that it would be difficult to access otherwise.*
> *(Biological research company)*

> *Diamond is the leading light source. It is extremely well managed, reliable, technically leading and convenient. We have accessed a number of synchrotrons, but Diamond is our source of 1st choice.*
> *(Pharmaceutical company)*

Surveyed industry users (n=24) revealed that they undertake research at Diamond for a variety of reasons, both relating to *existing* products and materials (e.g. increasing understanding, conducting quality checks, or looking to make improvements) and to *new* areas (e.g. developing new products, understanding new materials, assessing materials under new conditions, and / or developing new tests).

6.4. Scientific impact

6.4.1. Impact that cannot be monetised

Industrial

It is difficult to quantify levels of **industrial access** via the non-proprietary route because much of this takes place through academic institutions. However, analysis suggests that over a quarter (28%) of Diamond's academic users have collaborated or been sponsored by industry for work at the facility. Rolls-Royce, for example, has collaborated regularly with academic users at Diamond, in addition to its own proprietary work, to improve the performance and effectiveness of its products.

Some experiment time is also set aside for **proprietary access**, which is predominantly used by industrial partners. The proportion of beamtime delivered through this route (3 to 7% each year) is higher than at many other facilities. This work is performed under contract guaranteeing confidentiality, with results only available to the customer. This is a real achievement and was part of Diamond's overall strategy to "attract and support the very best research groups in universities and institute and drive even stronger engagement and support for UK industry."

A prime example of this is XChem, Diamond's platform for streamlined chemical fragment screening using X-ray, which allows up to 1,000 compounds to be screened individually in less than a week, including soaking, harvesting, automatic data collection, and data analysis. Developing a new drug is a complex process, which can take 12-15 years and cost in excess of $1 billion, and the pharmaceutical industry might have to screen millions of compounds before honing-in on one or two candidate molecules. Increases in the speed and capacity of screening at Diamond means that drug developers can test many more candidate compounds in order to find a greater number of promising leads, which in turn increases the likelihood of new medicinal compounds being identified. The financial value of this drug development efficiency to the pharmaceutical industry is hard to estimate. However, a study published in 2012 found that faster development times (specifically a 25% reduction across all phases) could reduce total costs for an approved drug by 16% (US$129 million)[12].

Another area of outputs mapped as part of this study is **patents.** There is evidence from a recent survey of 1,368 UK inventors that allows us to estimate the value of the 75 Diamond-related patents mentioned by the industrial users at £676 million (2018 prices)[13]. This represents an interesting assessment, however we felt limited by the low response level to validate the monetisation into the overall evaluation. We recommend that for a future evaluation more emphasis is given to engagement with proprietary users to obtain a more comprehensive dataset. An in-depth assessment of each patents could also more accurately map the contribution that can be attributed to Diamond.

International

Diamond delivers internationally leading synchrotron research and innovation. As part of the Technopolis survey, **academic user respondents (87% of 345) reported that Diamond was very important or critical for their research.** Most were also clear that, although there are often alternative sources and methods available, non-access to Diamond would have a range of negative implications for their research (e.g. increased costs and reductions in efficiency, quality and international competitiveness).

Nearly all the academic users surveyed (94% of 321) said that their use of Diamond had been beneficial for their national or international **reputation.** Most users also reported impacts on the international networks and reputation of their wider research group, as well as on the **attractiveness of the group** to other researchers and students. Most also indicated (more generally) that the existence of Diamond was very important or critical for the attractiveness of the UK as a place to conduct research.

Just over half of academic users reported that their use of Diamond had been very important or critical to their subsequent **ability to access grant funding** (the academic case studies alone include examples of Diamond-based research serving as the foundation for further grants from Innovate UK, the Engineering and Physical Sciences Research Council (EPSRC), Biotechnology and Biological Sciences Research Council (BBSRC), the Energy Technology Partnership (ETP), Advanced Propulsion Centre (APC), the Wellcome Trust and the Department for Business, Energy and Industrial Strategy (BEIS). The impact on **attracting industry contracts** was less widespread, but nearly half of academic users still claimed that there had been some benefit. Again, the academic case studies provide some examples e.g. in relation to nuclear decommissioning, Alzheimer's disease and metallic implants.

As mentioned earlier, in a recent analysis (2014-2018) carried out by the League of Accelerator-based Photon Source (LEAPS), over 10,000 academic users[14] from more than 50 countries are using Diamond.

Diamond has acquired a strong presence on the global stage and has attracted additional funding for the facility. A good example of the growing influence brought by Diamond is a recent grant award for Synchrotron Techniques for African Research and Technology (START).

It is funded by a £3.7 million grant by the UK's Science and Technology Facilities Council (STFC) from the Global Challenges Research Fund (GCRF). Diamond has many instruments relevant to meeting the scientific objectives of African researchers and through this grant will provide detailed access to instruments, training on undertaking the experiments and support in analysis and data interpretation. STFC awarded the funding from the GCRF, a 5-year (2016-2021) £1.5 billion fund that is a key component in the delivery of the UK Aid Strategy, ensuring that UK research takes a leading role in addressing the problems faced by developing countries through research and innovation. GCRF is a UK government fund that aims to promote challenge-led research, and which works towards strengthening capacity for research, innovation and knowledge exchange in the UK and developing countries. It supports partnerships between excellent UK research institutions and researchers in developing countries. GCRF is connected to the UK's Official Development Assistance (ODA) commitment, which is monitored by the Organisation for Economic Cooperation and Development (OECD).

SESAME is the first operational Synchrotron Light Source in the region and was set up with support from UNESCO to build scientific and cultural bridges across the Middle East. It started operations in 2016 and is providing vast scientific potential for scientists from the Middle East and neighbouring countries. SESAME's members are Bahrain, Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey. In 2018, Diamond secured a £1.5 million grant from the Department for Business, Energy and Industrial Strategy (BEIS) to foster collaboration between the two organisations, providing training and development support in the form of fellowships enabling SESAME staff to spend time at Diamond.

Finally, Diamond has been a catalyst in shaping Lightsources.org, which is the result of a collaboration between light source facilities from around the world, gathering 23 synchrotrons and 6 Free Electron Laser (FEL) facilities representing 24 organisations. They gather under a global online resource, providing information and updates about light sources research and achievements, and opportunities for skills development, careers growth and international collaboration. This is made possible by financial support from the member facilities ($80 thousand per annum), whose contributions enable further promotion and international coverage of their innovations and capabilities. Diamond has hosted the administration of the collaboration over the past 10 years and Lightsources.org has created one voice for the field, ensuring member facilities' impact is further maximised.

6.4.2. Protein Data Bank (PDB)

PDB data are **freely and publicly available**, without restrictions on usage, and the PDB archive is heavily used.

Another important role of the PDB is to make structural data available for reuse and integration in other resources. For instance, in 2018, a review of 1,737 active biological databases found that 429 utilised PDB data. These databases add value to PDB data and function as resources for protein-protein interactions, enzymes, metabolic pathways, signalling pathways, mapping cancer mutations in proteins, antibody structure, viral capsid structures, yeast genomics, drug-binding sites, and more.

An economic analysis of research analytics published in 2017 found that a reasonable estimate to replicate the PDB data archive at the time was $12 billion. From 1995 to the end of 2016, there have been 117,346 structures deposited in the PDB (total X-ray structures).

Since we cannot replicate that study with today's numbers, we must limit our data to structures solved before 2017. Using this limited dataset, we can determine the value of a single structure ($102,261.69) and estimate a total valuation for the contribution of Diamond to the PDB as well as a yearly valuation since 2009 based on the number of structures deposited each year by Diamond.

Before 2017, Diamond's contribution amounts to the PDB is 4,666 structures deposited. Which gives us a total valuation of $477 million or £352 **million**[15]. Please note that this represents around 45% of structures solved at Diamond.

In 2016 alone, the valuation of the yearly contribution is over $93 million or £68.7 **million**.

12 DiMasi, J.A. Pharmacoeconomics (2002) 20(Suppl 3): 1. https://doi.org/10.2165/00019053-200220003-00001

13 Note that 75 patents is an extrapolation from 24 respondents of which 50% indicated that they have or will submit a patent based on their research at Diamond. (25% have already submitted and 25% plan to submit)

14 Data from the user administration system submitted as part of a study carried out for LEAPS.

15 Average exchange rate for 2016 of 1.35415455 calculated from the data available from the Bank of England: https://www.bankofengland.co.uk/boeapps/database/fromshowcolumns.asp?Travel=NIxASxRSxSUx&FromSeries=1&ToSeries=50&DAT=RNG&FD=1&FM=Jan&FY=2016&TD=31&TM=Dec&TY=2016&FNY=&CSVF=TT&html.x=86&html.y=41&C=C8P&Filter=N

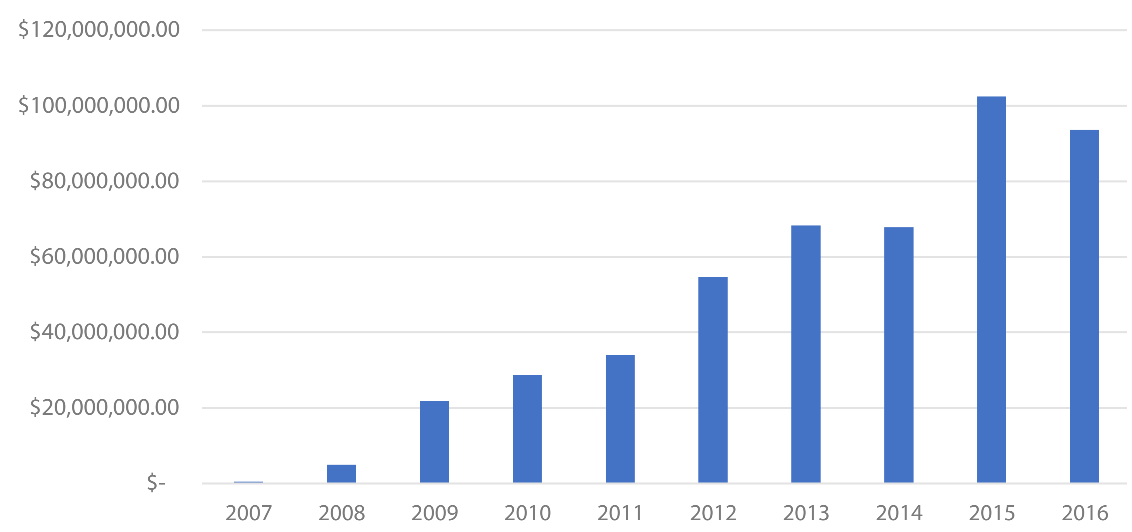


Figure 6-5: Estimated values of protein structures solved at Diamond based on the economic analysis published in 2017, hence the data ending in 2016..

6.4.3. Publications

Florio et al[16,17] propose measuring the production of knowledge by monetising the value of peer reviewed papers emerging from the direct or indirect use of a research infrastructure (i.e. conducting experiments or using the data emerging from experiments conducted by others), and also monetising the references (citations) that are made to those original papers. Specifically, the method suggests looking at the publications produced by users (P0) as well as the papers (P1) produced by non-users that are then citing P0 papers. The benefit of papers citing P1 in turn (i.e. P2 papers) are considered to be negligible and so excluded from estimation. **The advice is to then monetise those outputs by the taking into consideration the time it takes to produce and cite papers**, as well as the salary of the researchers involved in that process.

This study has employed a tailored version of this approach to make a first attempt at monetising the value created by the Diamond publications.

By first looking at 2019 papers and using the following parameters, we can establish an average value for Diamond publications for the year 2019. Then assuming a 1.85% inflation rate every year since 2002 we can estimate the value of knowledge produced by Diamond since the facility became operational.

16 Florio et al (2016). Exploring Cost-Benefit Analysis of Research, Development and Innovation Infrastructures: An Evaluation Framework. CSIL, Working Paper N01/2016

17 Florio el al (2015). Cost-Benefit Analysis of the LHC to 2025 and beyond. arXiv:1507.05638v1 [physics.soc-ph]

	Biology	Chemistry	Physics
Number of Diamond paper in 2019 (A)	433	351	333
Average time spent by research on actual research (B)	60%	60%	60%
Average Salary in the UK (C)	38526	32145	43605
Cost of employment in the UK (D)	30%	30%	30%
Average number of publications per year and per scientist (at least based on Diamond data) (E)[18]	1.4	1.44	1.44
Estimated time spent by co-author working on a single paper (F)	30%	30%	30%
Average number of authors per paper (based on Diamond data for 2019) (G)	9.82	9.1	9.52
Value of a paper for 2019 (V)	£76,267	£59,865	£84,191
Value of all 2019 papers for the given field	£33,023,793	£21,012,762	£28,035,658

Table 1: Parameters used for the monetisation of Diamond articles.

For 2019, this gives us an average value for 1 single article of £**73,441** and a total value of £**82 million** for all articles published in 2019.

Since beginning of operation in 2007, Diamond has been involved in the publications of over 9,600 articles which have a total estimated value of £**677 million**.[19]

The great majority (87%) of users indicated that Diamond was critical / very important to their research, so it is possible that most of the papers included in this analysis could not have been written in their existing form if Diamond had not existed. However, in a 'no-Diamond scenario', the time spent on producing these Diamond-related outputs would likely have been spent on other research and the production of other publications instead. As such, displacement – of types and number of outputs – is potentially high.

Diamond is therefore not necessarily generating additional outputs (publications) at the system level, but rather it is aiming to enable outputs that are of better quality (higher impact) and in different areas (including where research is not achievable by other means) than might otherwise be the case. We therefore expect this portfolio of Diamond-publications to support additional wider socio-economic benefits over time (which are not yet realised and / or cannot currently be captured), and are using the value of time spent creating these publications as an intermediate estimate of the additional (monetary) impact that Diamond will enable. Analysis of the extent to which this occurs would require analysis of the knowledge produced and its value to other researchers, as opposed to output production, with Diamond as well as the counterfactual scenario.

Further analyses of the bibliometric performance of Diamond research (2007-15) undertaken by its main funding agency STFC showed that the impact of journals in which Diamond publications appear is high (65% above average) and that the impact of the publications themselves is 59% above world average, with 11 citations each on average. In fact, 19% of Diamond publications belonged to the top 10% most highly cited in their field. **A more recent analysis is showing that the mean number of citations for the whole list of Diamond Publications has now reached 25.33 (source: Web of Science).**

Bibliometrics also show that Diamond plays an important role in fostering collaborations, with most papers (80%) involving two or more institutions. International collaborations tend to generate the highest citation impact levels – however, the impact of both UK-only and international collaborative **Diamond publications** were **well above global average**.

18 Fanelli D, Larivière V (2016) Researchers' Individual Publication Rate Has Not Increased in a Century. PLoS ONE 11(3): e0149504. https://doi.org/10.1371/journal.pone.0149504. Data extracted from the dataset 1. Social sciences are excluded. Average calculated over the first 15 years of research since first publication date for 35,029 authors from the United States, Canada, Europe-15 countries, Australia, and New Zealand.

19 Full calculation is available in Appendix F

As part of the STFC study, it examined **Diamond's impact** relative to other similar facilities (CLF, ISIS, ESRF and ILL). It was found to have **the highest citation impact** and the **highest percentage of cited papers** amongst the five. Diamond also **outperformed** the **UK baseline in nine of the fifteen research fields** examined and had t**he strongest performance overall,** amongst the facilities assessed, in all-but-one of the areas.[20]

6.4.4. Income from Industrial research

Diamond has an active programme of proprietary access, supporting both UK and global R&D companies with their research. Providing access and tailoring services to key UK companies has meant that Diamond is playing a part in the retention of R&D within the UK, helping its customers to retain their commercial advantage by having access to unique and world-leading technology.

As more beamlines have come on-line and more beamtime has been made available, Diamond's annual proprietary income has grown, from £300 thousand (2008/9) to over £3 million (2019/20), with fees dominated by pharmaceutical and biotechnology firms, as well as contract research organisations. Some **80-90% of this income** now comes from **repeat users**. Nevertheless, Diamond continues to work hard to engage with and support new companies, across different sectors, size-bands and geographies, with a number of new proprietary users engaged every year for the past decade.

Since 2008, the cumulative income from industrial users has reached over £**15 million.**

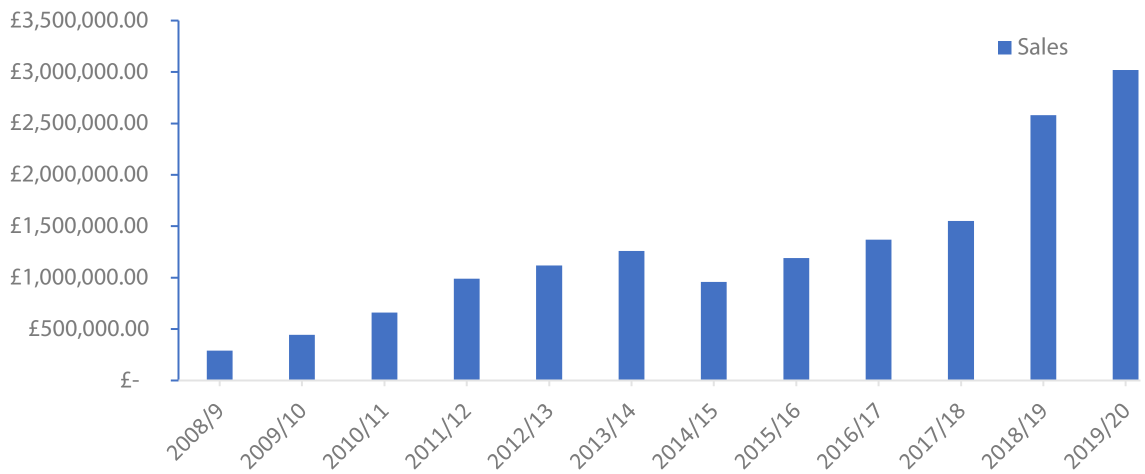


Figure 6-6: Volume of sales for industrial access

6.4.5. User valuation of beamtime at Diamond

There is a fee for time and services provided through the proprietary access route, and we can use this as the basis for inferring an implicit value placed by users on their direct benefits of Diamond beamtime. Individual fees charged are confidential and do vary (e.g. according to the level of advice or specialist equipment required), but Diamond report that these range from £525 to £800[21] per hour of beamtime paid by Diamond industrial customers. These figures are comparable with fees from similar facilities who have made the information available to us (e.g. PETRA III at DESY – Hamburg Germany). It also assumes that the market price paid for access to Diamond (which is also similar to rates at other comparable facilities) is a good indication of the value of this access to users. Applying these fees to total beamtime delivered (all academic access routes in 2016/17), gives a total valuation of £44.6 million - £67.9 million for the year 2016/17 for access to beamtime (and associated support) at Diamond.

20 CWTS report commissioned by STFC, 2015.

21 These figures are comparable with fees from similar facilities who have made the information available to us (e.g. PETRA III at DESY – Hamburg Germany)

Assuming that the fees are following the yearly inflation of 1.85% used for previous estimation, we can project the value for the whole period ranging from 2007 to 2020:

Years	Fees (low estimate)	Fees (high estimate)	Shifts Delivered (Agreed PBS) academic access routes	Hours of beam-time delivered to academic users (shifts x 8 hours)	Lower estimate direct benefits to users	Higher estimate direct benefits to users
2007/8	£443.78	£676.24	1 634.0	13072	£5 801 149.77	£8 839 847.27
2008/9	£452.15	£688.99	2 928.4	23427	£10 592 498.53	£16 140 950.14
2009/10	£460.67	£701.98	3 787.9	30303	£13 959 731.23	£21 271 971.40
2010/11	£469.35	£715.21	5 088.0	40704	£19 104 611.77	£29 111 789.36
2011/12	£478.20	£728.69	6 320.4	50563	£24 179 296.27	£36 844 641.93
2012/13	£487.21	£742.42	7 294.8	58358	£28 432 884.37	£43 326 299.99
2013/14	£496.40	£756.42	8 272.9	66184	£32 853 373.56	£50 062 283.51
2014/15	£505.75	£770.67	7 792.3	62339	£31 528 064.06	£48 042 764.28
2015/16	£515.29	£785.20	9 604.0	76832	£39 590 363.74	£60 328 173.33
2016/17	£525.00	£800.00	10 610.9	84887	£44 565 721.75	£67 909 671.23
2017/18	£534.71	£814.80	14 152.1	113217	£60 538 443.22	£92 249 056.33
2018/19	£544.60	£829.87	14 174.6	113397	£61 756 341.24	£94 104 900.94
2019/20	£554.68	£845.23	14 475.1	115801	£64 232 505.56	£97 878 103.72
TOTAL					**£437 134 985.07**	**£666 110 453.43**

Table 2: Estimated direct benefits to academic users by providing free access to the instruments

This gives us **a total estimated value of the direct benefits to academic users** of £551.5 million since the beginning of operation (if we average the values). Note that this is just a measure of the direct benefits to individual users and does not capture any of the wider spill overs of the research undertaken, or indeed other benefits arising from Diamond's existence.

Diamond regularly collects **user feedback** after each experiment and this shows a near unanimous positive rating to **users' satisfaction with Diamond services** (good/excellent reported by **97% of 1,681 respondents**). The socio-economic study explored further the reasons why users might choose to use Diamond, given that many could apply to alternatives or use other techniques.

Users highlighted:

- **Accessibility and availability of beamtime** - including the clarity and speed of application processes, and the range of access modes available (mail-in/rapid/block). Remote access in particular was widely praised, while industry was highly positive about free access for non-proprietary work
- **Overall quality of facilities** (source, beamlines, instruments) – with many aspects considered world-leading, and some instruments being unique (making Diamond the "only place" for certain research)
- **Location of the facility** - and the consequent ease, convenience and low cost of access, transportation and data collection. Most industry users also said it could play a role in any future location decisions
- **Level of expertise and support provided by staff** – including the professional, high-quality, expert, flexible and responsive nature of support, advice, technical assistance and collaboration provided

Users also saw Diamond as an **innovative facility** - both in technical capabilities and in the accompanying services provided, with the facility constantly looking to streamline the user experience, respond to changing needs, improve the quality of research and enhance the utility of outputs. Diamond has also pioneered capabilities which others have then followed. This includes offering remote access, which was first introduced for protein crystallography at Diamond and is now a feature of most facilities. It also led the way in the automation of beamlines – a model now being replicated across the world. The speed of experiments now possible on some beamlines (the MX group) means that they host over half of all experimental sessions at Diamond, with 70% of these visits now fully automated.

At the same time as some processes are becoming more automated, there are more innovative and novel approaches to experiments being developed elsewhere at Diamond. Indeed, as greater use is being made of automation and robotics, beamline scientists are being freed up to focus their efforts on more challenging or experimental measurements and experiments, helping to further develop future capabilities. In addition, whilst expertise surrounding synchrotron light has historically been distributed across academic users and based in universities, as the barriers to engagement have lowered, expertise has become increasingly concentrated within the synchrotrons themselves. The beamline **scientists and technical staff at Diamond** therefore often bring the **essential knowledge** and experience that is needed to enable the successful design, delivery and interpretation of experiments for users.

7. Technological impact

7.1. Technological inputs

As part of their strategy, Diamond has been focussed on driving forward its technical and scientific capabilities. As a result, this creates an environment where investment is key alongside people to deliver step changes required to drive activities forward. In this section, the inputs for technological developments are the same as the one for science (an investment of £796.2 **million** and over **750 staff**). For the overall assessment of the impact of the facility, it is important that those are not counted twice; however, we should still list them for this specific section.

7.2. Technological activities

7.2.1. Industrial R&D

Since 2008, the number of industrial customers using Diamond for their research has grown to over **180 companies**.

7.2.2. Internal R&D

The technical division employs over **200 staff** who are continuously working on the improvement of the machine and of the instruments. The division is made of the following groups:

- Accelerator Operations
- Accelerator Physics
- Diagnostics
- Engineering
- Survey and Alignment
- Insertion Devices
- Installation and Facility Management
- Power Supplies
- Radio Frequency
- Vacuum

Technology developed at Diamond often pushes the boundaries of what suppliers can do and sometimes result in outputs that were not necessarily anticipated leading to innovation in the supplier chain as reported in the technological output section.

7.2.3. Supplier based innovation

Due to the high technical specifications of Diamond's facilities, very high-quality instruments are often required and commissioned. This entails a great deal of collaboration, mutual testing and feedback as products are developed. In time, others will also pick up and apply similar technical changes and in doing so, push the whole field forward. Furthermore, certain suppliers can be very specialised and push the boundaries of the technology. This is particularly noted in the areas of optics and mechanical engineering, as they are regularly coming up with new ways of improving processes and products to support better beamlines. Some of Diamond's suppliers are especially important because they are the only company in the world that produces, or is capable of producing, the particular products needed. In others there may be just a handful of suppliers (and only ever will be, because of the size of the market).

Since its creation, Diamond has issued **non-construction contracts worth over £210 million**, providing a range of suppliers with additional revenue and creating new employment to service these contracts. Several suppliers responding to the Technopolis online survey (n=62) mentioned the important role that Diamond played in simply providing a regular and continuous stream of opportunities and income, supporting jobs and investment. One went as far as to say that "sometimes Diamond have ensured our financial survival", while another suggested that they would have relocated outside the UK if Diamond had not existed.

7.2.4. Computing and Software Engineering

Computing and Software activities

The strength of the computing capabilities and expertise available at Diamond is pivotal to the functionality and usability of both the machine, and the data experiments generate. As such, the computing activities of Diamond span the control systems and manipulation of hardware systems, to the creation of software to facilitate data capture, processing and analysis. There are several groups in place working on these requirements and Diamond employs many of software engineers and scientists to develop key software and applications.

The software developed at Diamond can essentially be separated into 3 categories:

- **Scientific software and applications** – software developed by Diamond's scientists and engineers to enable the efficient acquisition and analysis of data from our instruments
- **Technical software and applications** – software developed by Diamond's Scientists and engineers to manage and operated the synchrotron facility and instruments
- **Business software and applications** – software developed by software engineers to enable the business operation of the facility

Most of those applications are open source (free to use) and are co-developed within the science community.

Scientific software and applications

Diamond has developed **dozens of applications to support the science**[22] ranging from small applications to very large software framework and application collections. Two of the main groups responsible for delivering the scientific software are the Data Acquisition Group and the Data Analysis Software Group.

The Data Acquisition Group is responsible for providing the software that drives most experiments at the facility, and for providing support to those beamlines still under construction or commission. Data generated by the instrumentation and Diamond is acquired by a Generic Data Acquisition (GDA) system. This software, initially developed at SRS Daresbury, has since been adopted and continually developed by Diamond's Data Acquisition Group. The primary aim of the GDA is to provide a generic and flexible software framework that can be adapted to any beamline and hardware control system.

The Group is also responsible for developing the experiment automation software. This is a key aspect of increasing the speed of experimental processes and so increasing user's productivity. Automation is a valuable aspect of Diamond's offering and allows certain beamlines especially in the life sciences area to run experiments entirely unattended. Users send their samples to Diamond and log into Diamond's computing system to monitor their experiments. An ensemble of robots coordinates the data collections and analytical pipelines provided by the Data Analysis Group, delivering the final results to the users without them ever needing to be physically present.

22 A non-exhaustive list of scientific software developed at Diamond is given in Appendix F

The Data Analysis Software Group develops software and analytical processes to derive knowledge from the data generated by Diamond. Working closely with software and computing groups across Diamond, and with external collaborators, the group has developed a suite of open source software tools to optimise data visualisation and associated calculations. The Data Analysis Group has also developed software pipelines for processing and analysing data for a range of different scientific techniques, allowing users to process their data with little manual intervention. Diamond has also, created a software platform called DAWN to provide data visualisation, processing and analysis, calibration, mapping. This platform is again open source, so that others can contribute to it and benefit from reusing it. The platform, and its components are applied to solving further problems and utilised to produce bespoke tools for beamline specific analysis.

Technical software and applications

To operate and control the synchrotron, a team of around 30 staff at Diamond are responsible for the control systems supporting machine operations and the beamlines. This includes software engineering, systems engineering and electronic design.

They have developed **dozens of applications and manage hundreds of industrial controllers**[23].

Business software and applications

Given the large amount of data collected by the facility, it follows that Diamond is also involved in developing data management tools and services. These includes the portal through which users are able to access their data. This portal was developed as part of the EU funded PanDATA ODI initiative, a European wide initiative to provide a single point of access to data from multiple facilities. Other methods of accessing data generated at Diamond are also being developed, such as the SynchLink app, used for accessing information collected and processed on Diamond MX beamlines.

Development hours

As of August 2020, there were around 80 software engineers and scientists at Diamond which can be roughly sorted into the following categories: Graduate Software Engineer, Senior Software Engineer, Senior Software Scientist, Software Engineer, Software Scientist, Software Systems Engineer, Other.

Assuming they work on development 80% of their time (the rest being support and meetings) and excluding the other software staff who are mostly in management we can deduce the following activity table:

Year	Role	FTE	Produces code	Time spent on development	Productive hours per year
2020	Graduate Software Engineer	13	yes	80%	17550
2020	Senior Software Engineer	21.67	yes	80%	29262
2020	Senior Software Scientist	6	yes	80%	8100
2020	Software Engineer	11	yes	80%	14850
2020	Software Scientist	19	yes	80%	25650
2020	Software Systems Engineer	10	yes	80%	13500
2020	Other	14.1	No	0	0

For 2020 this corresponds to over 108,900 hours of development work. Using legacy reports from HR we extracted the number of FTE staff producing software since 2011 and estimated the number of FTE staff producing software between 2010 and 2011. Using this data, we can estimate that as many as **670,000 hours** of development work has been done by Diamond employees.

23 A non-exhaustive list of technical application developed at Diamond is given in appendices 11.3 to 11.5.

7.3. Technological outputs

7.3.1. Academic users' output

A minority of academic users (15% of 303) also reported that their research using Diamond had already led to one or more innovation-related outputs, including new consultancy and industry contracts (11% of respondents), new products, services and processes (8%) and new patent applications (5%).

Additional analysis of the **Lens.org patent database carried out in 2020** has in fact identified a total of 941 peer reviewed publications with patent citations, where 1 in 10 publications is linked to a patent. Additionally **a total patent citation count** of **3,455** has been achieved (this means that a single publication has been cited in multiple patents). The number of citing patent applications each year has tended to increase over time. More than 10% of Diamond publications have been cited, which are spread across a range of fields including organic chemistry, medical science, biochemistry and the area of measuring and testing. We estimate that these patents are collectively **valued at £10.2 billion** (in 2018 prices). The exact criticality of Diamond in each case is unknown – but some proportion of this considerable sum can be 'claimed' by Diamond. A conservative estimate of this proportion is around 1%, which would mean that the contribution from Diamond could be worth at least £103 million[24].

There are several examples of innovations and commercial benefits within the study's academic user cases. This includes two where new **start-ups** have resulted directly from Diamond research:

Professor Alberto Saiani (Manchester) - Diamond was used to help craft and study self-assembling peptides to produce a range of hydrogels. Industry and academic demand for these led to the creation of Manchester BIOGEL (Peptigel Design), which offers a range of self-assembling peptide hydrogel products for use in 2D/3D cell culture, 3D bioprinting and incorporation into medical devices.

Jon Sayers (Sheffield) - Diamond was used to precisely define the mechanism by which FEN enzymes maintained the double helix structure of DNA by trimming unnecessary "branches" during replication and repair. As DNA replication occurs in all life, FENs could serve as novel targets for antibiotics or anti-cancer therapeutics and understanding this mechanism is a key part of future drug development.

DeFENition Ltd was founded in 2016 to identify small molecule inhibitors of FENs to tackle antibiotic resistant bacteria. The research at Diamond helped demonstrate that this was based on clear and sound scientific foundations, which was crucial in securing an initial investment of £400 thousand. By December 2017, DeFENition had secured a further £1 million of investment, including for follow-on research.

Such start-ups provide an important role in the economy. Recent analysis by the Enterprise Research Centre found that of 240,000 UK firms born in 1998 (mostly employing fewer than 5 people), the top 2,000 in 2014 were employing 110,000 people (55 each on average) and generating around £16 billion in sales (£8.5 million each on average). Around half were also selling internationally – a higher proportion than for the economy as a whole (20%). A separate analysis by the CEBR a year later estimated that there were 589,000 start-ups with employees in the UK in 2016, with a direct employment footprint of 3.4 million people, and contributing £196 Bn directly to UK economic output.

It is also worth noting again the Protein Data Bank mentioned earlier to which Diamond is a major contributor with 10% of all structures deposited globally for the period 2010-19. The structures that are openly available through this repository have significant applications for structure-based drug discovery and have contributed to the development and launch of new drugs. For example, a study published in 2018 found that the discovery and development of 210 new drugs approved by the US Food and Drug Administration (2010-2016) was facilitated by structural information distributed via the PDB.

24 The PatVal EU project surveyed European inventors to explore the value of European patents. Based on the 1,140 patents now found with Lens.org, using their methodology these are valued at £10.2 billion and 1% (£103m) is attributed to Diamond.

7.3.2. Internal research technological output

More than 1,000 publications in the Diamond publications database are related to technical developments. These include both peer review journal publications and conference proceedings. This demonstrates well that Diamond has delivered and will continue to deliver on its strategy to "provide a highly reliable, high performance source of X-rays, ultraviolet and infrared light and offer world leading beamlines and analytical tools."

Diamond itself is engaged in collaborative work to develop new technologies. Its collaborative research continues to grow significantly, with more than **2,500 research contracts** having been entered into, which include facilitating access for more than **1,000 scientists** with "Visiting Scientist" status, more than **150 formal research collaborations, 45 joint appointments**, secondments and fellowships and more than **100 licences** arising out of this research. For example:

- Diamond collaborated with the Medical Research Council in developing the CombiPuck™ system for crystallographers to use to send crystals to facilities. This is now commercially available through a licence with MiTeGen (e.g. the basic CombiPuck™ cup and lid retail at $450)
- Diamond developed the F-switch, and F-Switch Manipulator, which have successfully been used at Diamond since 2015 and are now also licensed to a third party for manufacture and sale
- Diamond helps to develop read-out ASICs, which have been exploited further to enable the building of full X-ray cameras. One of these cameras has been licensed to a UK start up
- Diamond has helped to develop a number of software tools and platforms for data acquisition and analysis, including the data visualisation, processing and analysis software DAWN. This open source software has been downloaded 2,000 times in the past year alone and is used on beamlines in Spain and Germany, in addition to being used for automatic processing on nine beamlines at Diamond

The technological requirements of Diamond have also resulted in **spin-off** companies. This includes: **Quantum Detectors**, which takes proprietary detection systems and technologies developed out of advanced research and turns them into more easily accessible systems to benefit the wider scientific community.

7.3.3. Supplier based innovation developed

Diamond's supplier organisations were asked through surveys about various possible **positive effects on their organisation** that have resulted from their past sales to the facility. Aspects asked about included their ability to work successfully with public research institutes, their in-house technological capabilities, their capacity to innovate and the price performance of their products. The feedback provided was positive, with a majority (70%+ of 57) reporting some improvements in each of these areas.

Hivac (specialist vacuum chambers), **Orbital Fabrications** (welding and fabrication), and **DECTRIS** (X-ray detectors) all described how Diamond issues ambitious and demanding specifications for its contracts and explained how this has encouraged them to improve both product quality and internal capabilities. In the case of Hivac, they have found other applications for the new and improved products developed for Diamond.

The sample of 62 suppliers replying to the survey also reported a number of specific **innovation-related outputs** resulting from their work with Diamond. This included: 2 new licence agreements; 13 new products and services; 7 new processes; and the launch of 1 new start up.

7.3.4. Internal software developed

The time spent by developers to produce various software applications is a substantial activity at Diamond. Outlined below is a list of some examples of the software applications developed at Diamond and used every day by Diamond's users and Diamond staff:

Scientific software and applications

Generic Data Acquisition (GDA)

Data acquisition at Diamond is performed on almost all beamlines using the GDA software that provides a graphical user interface customised for particular scientific techniques (Fig. 2) and a server that is configured to work with the hardware on each beamline.

The GDA project is an open-source framework for creating customised data acquisition solutions for a science technique whether for neutron or X-ray sources. The software is developed in Java and the Eclipse RCP framework. It is free and released under the GPLv3 license.

GDA was initially developed at SRS Daresbury but since 2003 it has been adopted by Diamond Light Source who took over as the principal developer. GDA is intended to be applicable for any beamline on any synchrotron facility.

The Data Analysis WorkbeNch (DAWN)

Synchrotron light source facilities worldwide generate terabytes of data in numerous data formats from a wide range of experiment types. DAWN was developed to address the challenge of providing a single visualisation and analysis platform for data from any synchrotron experiment (including single-crystal and powder diffraction, tomography and spectroscopy), whilst also being sufficiently extensible for new specific use case analysis environments to be incorporated (e.g. ARPES, PEEM).

The DAWN project developed from the merger of two complementary data visualisation and analysis projects, Scientific Data Analysis (SDA) and Data Analysis Work Bench (DAWB). SDA was produced at Diamond in 2010, using visualisation components which became available as part of the process of GDA changing to the modular Eclipse RCP structure. DAWN was developed in the same year, on the back of a long history of Eclipse RCP development at the ESRF, but based on GDA's dataset model allowing the user to view data, set up experimental workflows and run custom analysis routines written in Python. The source code of these two projects was merged in early 2012 forming the initial version of DAWN.

Technical software and applications

EPICS

The Diamond facility is made up of tens of thousands of pieces of hardware. They extend from a simple temperature sensor, to precision power supply to complex detector. They all need to be controlled, monitored and orchestrated in a coordinated way. To achieve this hardware is abstracted into software using the control system tool kit called EPICS. This provides a software bus for other applications such as GDA to communicate with the hardware. EPICS is Open Source software originally develop by ANL and LANL, is now applied to control some of the world's largest scientific projects. Diamond is active contribute to the development of EPICS software components.

Diamond uses commercially available Programmable Logic Controllers (PLC) which are simple computers which can run application specific software in secure and reliable way. These are used for repetitive tasks such as interlock monitoring, machine protection and sequencing.

Business software and applications

ISPyB

ISPyB is a Laboratory Information Management System (LIMS) combining sample tracking and experiment reporting at synchrotron beamlines.

It has been used and developed by Diamond for all of the MX beamlines since 2007, and is increasingly being applied to other scientific techniques, including electron microscopy.

It was initially developed through a joint ESRF/e-HTPX initiative in 2003.In 2017, a collaboration agreement was signed for the development of ISPyB between the major synchrotron facilities in Europe. Today ISPyB is actively used and further developed by the following partners: ESRF, Soleil, DLS, MAX IV, HZB, EMBL, Global Phasing Ltd, ALBA.

7.4. Technological outcomes

7.4.1. Benefits of computing at Diamond

Various stakeholders interviewed by Technopolis highlighted the fact that the analysis and interpretation of data is one of the more challenging parts of experimental work, and that therefore the software tools, training and expertise provided by Diamond in this regard are a very important part of the facility's overall offering. In addition, the ever-increasing volume and complexity of data will only further increase the criticality of these capabilities and expertise going forward.

Academic users

The Diamond user feedback form also asks for ratings of various aspects of the facilities and equipment. This includes source reliability, quality of beamline equipment and the quality of **beamline control and acquisition software**, among other aspects. **A majority (55%+) of users (n=1681) responding in 2016/17 have rated each as excellent, while nearly all users (90%+) have rated it as either good or excellent.**

Industry users

Industry users were asked by Technopolis during the survey (n=21-22) why they might choose to use Diamond rather than another facility. More than 60% of the respondents put forward the quality and reliability of the facilities available; the respondents notably mentioned the beamlines, equipment, **computation technology/software and robotics – all of which were referred to as being "excellent", "state-of-the-art" and "world-leading"** (n=14).

Usage of software

Analytics regarding software usage is not easily available, however we have data regarding DAWN (previously mentioned in 7.2.4 and 7.3.4). In the past year alone (July 2018 – July 2019), the website has had 15,000 page views (12,000 unique) and the DAWN application has been downloaded around 2,000 times. Beyond Diamond (where DAWN is deployed for automatic processing on nine beamlines), the software is also now used on beamlines at the ALBA synchrotron (Spain), DESY (Germany) and BAM (Germany).

Global benefits

In summary, the most concrete benefit of such high level of computing activities and knowledge at Diamond is the ability to support all the science undertaken at Diamond. In effect, the computing facilities at Diamond are supporting thousands of users' proposals each year as well as their experiments from data collection to data analysis and data archiving with **over 20PB** of archived data up to 2020.

Furthermore, development work undertaken at Diamond also has benefits beyond the organisation as demonstrated by the adoption of software packages such as GDA/DAWN by other facilities.

Supplier based innovation developed

Many supplier companies have seen wider commercial benefits. For instance, Diamond is widely recognised as a prestigious client that expects high standards from its suppliers, and this can bring reputational benefits to those selected to work with the facility.

The Technopolis survey of suppliers confirms that one of the most widespread and important impacts of supplying Diamond is the **reputational benefit** that this brings, with **most suppliers** (81% of 54) **reporting that past sales** to Diamond had contributed to **the reputation or brand value of their business**. Indeed, many took the opportunity through the questionnaire to further highlight the importance of sales to Diamond in attracting other business. They mentioned the world-leading, prestigious nature of Diamond as an organisation, as well as various other factors:

- The exposure their products get (to those visiting and using the facility)
- The credibility that comes from being a trusted supplier of Diamond
- That Diamond serves as a useful and importance reference for other customers

That working with Diamond provides a route into wider markets

7.5. Technological impacts

7.5.1. Impact that cannot be monetised

It is true that for a place like Diamond there are many technological impacts that cannot be monetised. For decades, the synchrotron community worldwide has been benefitting from developments in hardware design, software, engineering, diagnostics and machine physics. Diamond is no exception; these areas above and beyond the science have played a key role in bringing together people from different nations, backgrounds and culture and has been a core element in what is often called science diplomacy.

7.5.2. Value of software developed

One potential way of evaluating the value of the software developed at Diamond, is to look at the total amount of time spent on software development and multiplying it by the market value of one hour of software development provided by external consultants and specialised organisations.

Data provided from the procurement department shows that the market rate for Software Engineers in 2020 ranges from £40.59 to £82.00 per hour. For Senior Software Engineers, the rate ranges from £49.20 to £130.00.

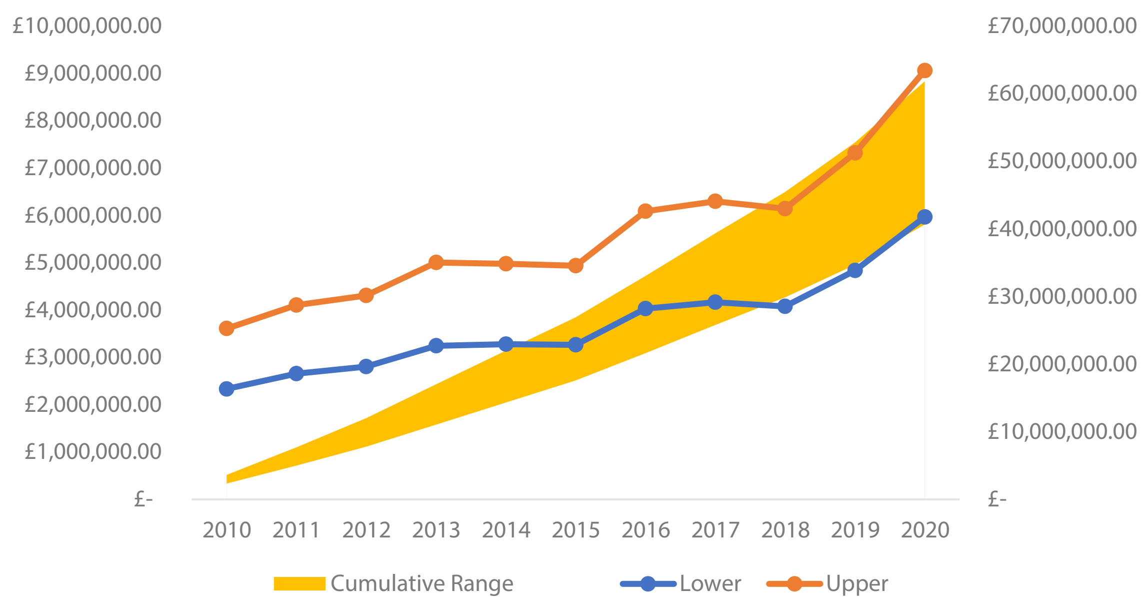


Figure 7-1 - Value of software developed at Diamond based on market rate for development hours. Data for 2020-2011 was provided by the HR department, the data for 2010-2011 is a backwards projection assuming 5% yearly growth of activity.

For 2020, this would give us a valuation for software and applications produced ranging from £**6 million to** £**9 million**.

Using legacy reports from HR we used the number of FTE staff producing software since 2011, and by applying a constant inflation rate of 1.85%, we can estimate **a total value for the software and applications produced at Diamond of £51.3 million** (if we average the upper and lower estimates)**.**

This must be seen as a very conservative value as most software is developed collaboratively and so other members of the collaboration contribute development effort; as well as gaining benefit. The result though is a piece of software for which the total value is considerably greater than the figure estimated based on Diamond's staff being the sole contributor.

7.5.3. Supplier based innovation impact

We asked suppliers about the **contribution of their sales** to Diamond to wider commercial benefits (i.e. beyond the increased income directly resulting from contracts with Diamond). A majority indicated that there had been some impact on each of the elements listed (which included competitiveness, income, market share and profitability), although for many the contribution was felt to be 'small'.

When asked specifically to estimate any increase in sales to other organisations that was attributable to past work with Diamond, only a handful were willing or able to respond - suggesting figures ranging from £100 thousand to £750 thousand in additional sales (£100k, £150k, £250k, £500k and £750k). Across these five firms, additional sales attributable to Diamond totaled £1.7 million, or £350 thousand each per on average.

If we apply this (1:2.4) ratio to a wider set of 899 higher-value (>£50 thousand) contracts for non-generic activities (i.e. excluding furniture, storage, insurance) awarded between 2003 and 2017, we arrive to a total estimate of £757 **million in additional turnover** (i.e. beyond the value of the contracts themselves) generated amongst suppliers for this 15 year period. On an annualised basis, this equates to a net direct impact of £50.5 million in additional turnover, including £6.2 million in additional profit, each year. This represents an interesting assessment of the impact linked to innovation from suppliers, however we recognise that given the very limited size of the respondents' sample, it cannot be included into our overall evaluation. This is however an area for recommendation were an increase engagement with the supplier base will lead to more a robust data set. This assessment could be done in the future.

Within the supplier cases there are similar benefits evident. For instance, a track record of supplying Diamond has helped these organisations to enhance their reputation and reassure potential clients of their expertise and capabilities, or has helped to open up entirely new markets:

Kurt J Lesker (vacuum technology) - Working with Diamond has increased exposure and accelerated their traction into other European projects. This has resulted in around £100k of increased sales.

Faraday Motion Controls (high performance systems) - The references provided by Diamond have been very valuable, helping to enhance reputation and gain access to new markets. Annual sales to other facilities have increased by ~£750 thousand and this is unlikely to have been achieved without Diamond.

Orbital Fabrications (welding) - Diamond's high standards have encouraged and stimulated Orbital to improve the quality of their products and their internal capabilities. The company has also benefited from being associated with the facility, which is looked upon positively by new clients.

The **Hexapod**, although not one of the full case studies developed for this study but part of the desk research, provides another relevant example. Diamond developed the Hexapod, a support system for mirrors, in collaboration with FMB-Oxford. It took them several months to develop the Hexapod with four subsequently installed on the I06 beamline. The company also supplied a further four Hexapods for other instruments at Diamond. Having demonstrated the success of this new product, **FMB-Oxford** then went on to sell a further ~20 Hexapod systems, mostly to other synchrotrons, generating **sales in excess of £2 million.**

8. Societal impact

8.1. Societal input

From inception, Diamond has been committed to engage and inspire the public through the science produced by the facility and use its unique offer to engage with a wide audience. As described in the science section, Diamond has applications in a wide range of disciplines and has strategically positioned itself to be an agent of change on the 21st Century global challenges.

Once again, the inputs for the societal impact assessment are the same as the one for science and technology (an investment of £796.2 **million** and **over 750 staff**). Diamond has a symbiotic relationship with its user community whereby the facility wants to drive its technology to the service of its user community and help them answer the best scientific questions. It does so through a thorough peer-review process held twice a year. As Diamond is actively involved in virtually all fields of research, it can reach the interest of many audiences.

There are several ways to disseminate and engage the public in the many facets offered by the user community from its diverse science, engineering, computing and many other disciplines behind the facility.

Longitudinal studies to observe some of the changes brought by these societal activities would require additional resources and strategic collaboration with for example the UKRI-ESRC.

8.2. Societal activities

8.2.1. Public engagement

Diamond has strategically focused efforts to engage and inspire the general public through promoting science. Diamond has also been working towards an objective of widening participation and diversity.

Diamond hosts a number of **outreach and public engagement** activities, which in 2018/19 alone attracted over 6,000 visitors, including university students, schools and members of the public. Some of the largest events are the Inside Diamond days, when Diamond is opened to the public with a tour and opportunity to visit. The engagement of secondary school students is also a growing area for the facility, with open days for A-level students and events exploring careers and opportunities in science, engineering and computing.

A large part of the programme is centred on a core programme of event days that invite various groups to the facility with Diamond staff and users giving talks and tours. However other wider activities are also carried out. A log of activities is held centrally for the purpose of reporting, which was useful in mapping levels of activities.

Typical Core Programme of Events		Core events with partners		One-Off Type Activities, including
Open days for the public	4 one day events per year	Science workshop events for schools (girls only)	Annual one-day event	Online careers tours/ activities with the Open University (2019-20)
Open days for schools	4 one day events per year	Engineering work-shop events for schools	Annual one-day event	Project M – 1,000 schools participating in a beamline experiment (2018)

Typical Core Programme of Events		Core events with partners		One-Off Type Activities, including
Talks and webinars for schools	Typically, 4-5 external visits/year, 11+ webinars in 2020	Computing workshop events for schools	Annual one-day event	Development of a Visible light beamline facility (2019-20)
Visits for General interest groups	12 evening events per year	Particle Physics Masterclass events for schools	Annual four-day event	Large scale family and public open days (Typically multi-day events every 3-4 years)
Schools work experience/ summer school placements	Annual 5-day programme for 20-30 students	Stargazing event for the public	Annual evening event	Careers fairs and events (2-3 one day events per year)
Various festivals	Big band–SE, Bluedot, If Oxford, Chelmsford etc) (Typically 3-4 events per year, lasting 1 -7 days	Supporting Big Science Event with Science Oxford for primary schools	Annually since 2019	Teacher CPD events (Every 2-3 years)
Staff Family Events	Annual one-day event			

In addition, Diamond also produces a large number of online and physical resources that can be used by others including online talks and tours, online simulations etc. Finally, Diamond offers **ongoing** training to students and staff, including: public engagement training, tour guide training, interview training, careers support (for schools).

8.2.2. Training and workshops activities

Diamond is involved in a range of training and outreach activities. It has partnered with many Doctoral Training Centres across several Research Councils and delivers shared Diamond studentships, training and workshops, as well as training 'on the job' as part of experiments at the facility. Some of the training events run at Diamond are recurring events, such as the XAS Workshop or the Small Angle Scattering Training School, while others are conducted on an ad hoc basis or in association with particular events. The training days and workshops cover a range of different topics, and range from training for the use of a specific beamline, the capabilities within a science group, the use of the supporting software for data collection and analysis, or any of the related instrumentation or processes required for effective use of the facility.

Doctoral training centre visits	Software training
Beamline training	Collaborative Computational Project visits
Conferences	Data processing training
Summer schools	University student visits
Synchrotron radiation users meetings	Sector specific workshops/symposiums
Teacher training	

Table 3: List of main training activities undertaken by Diamond

8.2.3. Student activities

Each year Diamond recruits a minimum of two Advanced Engineering Apprentices onto their IET accredited apprenticeship programme and Diamond is committed to identifying opportunities to recruit apprentices into other apprenticeships for example metrology. Annually Diamond also opens an internal process to encourage its employees to upskill via an apprenticeship and has a number of employees currently undertaking an apprenticeship from Level 4 (HNC) to Level 7 (master's degree). Such capabilities are in great demand, with shortages of STEM skills[25] (some 173,000 workers) costing UK firms £1.5 billion a year in recruitment, temporary staff and additional training.

Student engagement at Diamond encompasses the following programmes: Undergraduate **Summer Placement** students, Undergraduate **Year in Industry** placement students and joint **PhD students**. The programme is responsible for supporting around **90 PhD students** hosted at Diamond as well as supporting the recruitment of **30 students** per year in the undergraduate placement programmes developed by the organisation.

In a typical year, the Diamond handles more than **120 proposals** to the student programme including 60-80 for joint PhD studentships from external PIs, resulting in roughly 18 new studentships approved. There are typically 23 Diamond supervisors involved with a cohort of 18 students. The rest of the proposals are internal proposals for the Undergraduate **Summer Placement** and **Year in Industry** placements. Around half of those proposals are approved each year resulting in actual student placements. Applications to the PhD positions are managed in partnership with universities. The undergraduate placements formal application process receives several hundred student applications each year. In 2019, for the 2020 cohort of students, Diamond received **188 applications** for the **Year in Industry** placement and **656 applications** for undergraduate **Summer Placement** positions. After careful selection 49 candidates for **Year in Industry** placements and 78 candidates for **Summer Placements** were invited for interviews and given the opportunity to visit the facility in partnership with the public engagement team. Over 20 Diamond staff were involved with the **Year in Industry** candidate selection and interviews and over 30 staff involved in the **Summer Placement** programme.

Diamond is also engaged with a number of Centres for Doctoral Training (CDTs) and Doctoral Training Programmes (DTPs). We were approached by 30 schemes for letters of support and 26 letters were issued detailing Diamonds commitment to developing the next generation of scientists. This has resulted in a commitment to 9 funded studentships with CDTs/DTPs. In addition to studentships, in several cases Diamonds support for CDTs/DTPs includes commitment of Diamond staff time. There are 11 **scientists** included on advisory boards/steering committees and **15 senior scientists** included in direct teaching/ lecturing commitments for the CDTs/DTPs.

Activities for PhD students

Regular review meetings are held with the students to monitor their progress and provide support when needed. Diamond PhD students are encouraged to take part in and attend the numerous seminars and lectures that take place on the Harwell campus. They also have the opportunity to take advantage of training, symposiums and conferences taking place at Diamond, to further develop their skills.

Activities for Undergraduate students

Undergraduates on both of these placement schemes work on their own project, with support from their supervisors, collaborating groups and staff all across the organisation. In addition to their individual projects, students are given training in many areas to expend their professional development including presentation training and public engagement. Talks from a variety of current Diamond employees, who have had different career paths, are arranged for the students to attend.

Students activities could have been mapped under academic activities however we felt that the skills agenda fitted better within the societal scope, but we appreciate that there are arguments for listing them within the scientific section.

8.2.4. Press and media activities

The Diamond communications team continuously engages with Diamond staff and users to promote and disseminate the science undertaken at the facility.

Since May 2006, Diamond has published over **440 news articles, 415 science highlights** as well as around **100 featured articles** on its website. The number of news articles published on the diamond website averages at 33 per year since 2010.

25 https://www.stem.org.uk/sites/default/files/pages/downloads/stem-skills-indicator-findings.pdf

8.3. Societal outputs

8.3.1. Public engagement outputs

Outputs here only include the events undertaken by Diamond and not the resources developed over time. They do not include engagement with undergraduate or graduate students as they are covered elsewhere in this report.

As part of a Diamond desk research analysis, outputs for public engagement were mapped and reviewed. This analysis excluded VIP, stakeholder, academic or students beyond 18+. The information was evaluated over the period of 5 years from April 2014 – April 2019, looking into audience type and the quality of the engagement, thereby providing an idea of how much impact is being generated through the activities in place.

The following categories were defined: Teachers, Primary, Secondary, Adult, Family. For each group we looked at the number of events aimed at that audience and the number of interactions (i.e. the number of people interacted with at each event)

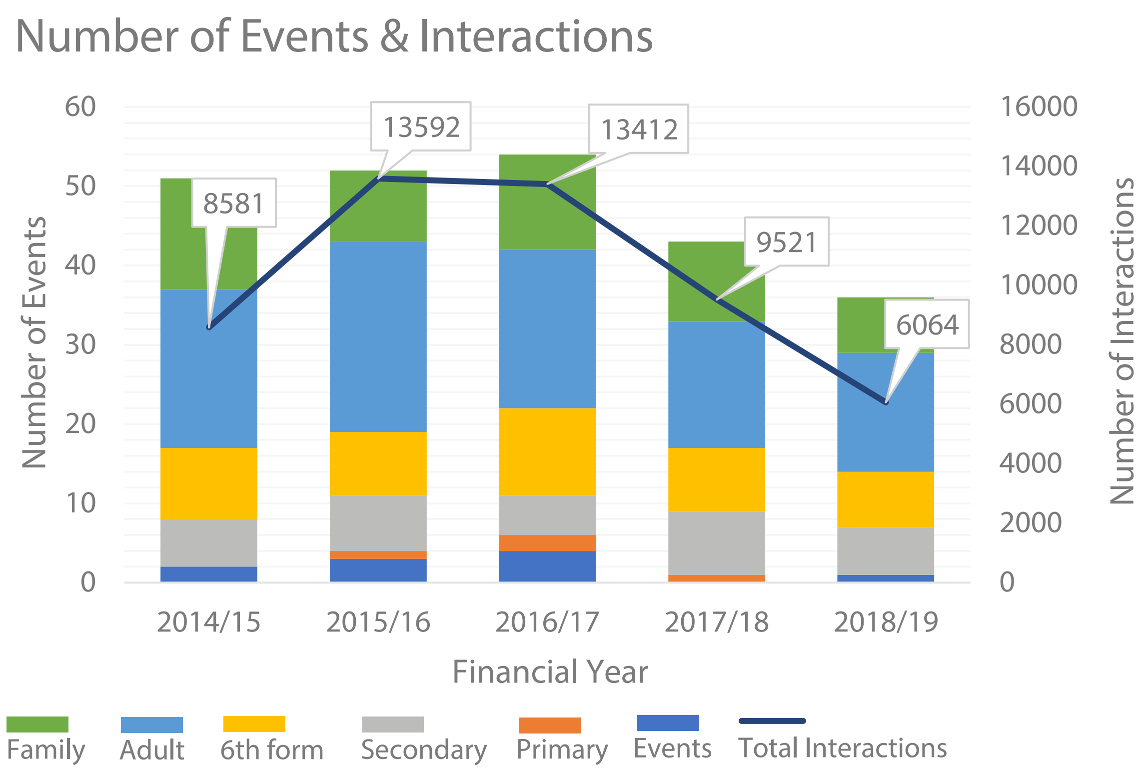


Figure 8-1: Number of events and interactions per category of groups engaged

8.3.2. Training and workshops output

Data from Diamond on training in the 2013-20 period show that 181 events were held in total, involving 430 training days. Across these events there were 7,668 attendees who received 19,191 days of training collectively. Nearly half of these days (8,347) are accounted for by PhD students.

Financial Year	Training events held	Total training days	Total attendees	Total attendee training days	Attendees who are PhD students	Total PhD training days
2013/14	19	36.5	451	611	189	284
2014/15	37	92	1,257	3,442	501	1,822
2015/16	36	74	1,304	2,749	636	1197
2016/17	29	71	1,739	4,825	535	1,931
2017/18	15	42	766	2,174	279	728
2018/19	18	54	886	2,581	442	1,464
2019/20	27	61	1,265	2,809	411	921

Table 4: Summary of training days delivered by Diamond. Source: Diamond. Note the same individual may attend multiple events within the same year, or across the period covered, but these are counted as separate attendances within the statistics.

Furthermore, the delivery of this knowledge as part of training and workshops leads to the development of Diamond's own staff through mentoring, training and support provided as part of these interactions. For each training or event delivered on average 6 STEM specialists are involved meaning that over the 2013-20 period looked at over 1,000 engagement opportunities have been fulfilled by these specialists.

8.3.3. Student engagement output

Diamond's student activities result in a qualitative engagement with undergraduates and postgraduates as follows:

Diamond offers **PhD studentships**. Available across a wide range of scientific and technical areas, these studentships are co-funded by Diamond with their host university, with an expectation that the student will spend around half their time at the facility. Diamond has hosted **149 students** who have successfully completed their PhD studentships; currently there are **97 current active PhD studentships**. On average Diamond recruits about **20 new PhD students each year**.

Work experience placements are also available for those studying for undergraduate degrees (degrees in science, engineering, computing or mathematics). These are mostly 12 months 'Year in Industry' placements which sees about 12 students every year, and has so far welcomed **46 students since 2016**. It also includes between 14 - 19 paid summer placements, lasting 3 months. Overall, Diamond has been able to offer these summer opportunities to **62 students since 2016**.

PhD students within **Diamond's user community** also conduct research, which inevitably involves some training by beamline scientists and other staff. The number of PhD student users each year has steadily increased over time. To date, students and early career represent some 30% of the user community. In 2016, Diamond surveyed PhD students (540 out 2,500) that had sourced data from the facility, over 80% of students' PhD theses contain data collected at Diamond. Another **80% of respondents** (80% of 540) claimed that the data collected at **Diamond was useful or absolutely crucial** to their PhD, **thus supporting the impact of the facility on the wider skills' agenda**.

8.3.4. Press and media output

Diamond media coverage

A media analysis examined for the financial year 2018/19 shows that Diamond itself was featured 444 times online across 32 countries within the past year (2018/19), with nearly half of these items accounted for by UK-based media outlets. Over the same period there were also 136 items relating to Diamond in UK broadcast media.

Diamond is hitting above its weight in terms of media dissemination, but these effects are hard to monetise.

Diamond Publications

A desk assessment using Altmetric software was carried out to map the reach of Diamond's 9,697 publications to date. Out of those publications **8,085 are currently tracked by Altmetric** and **6,615** have **mentions** attached to their records. Overall altimetric reports **83,732 mentions for the dataset**.

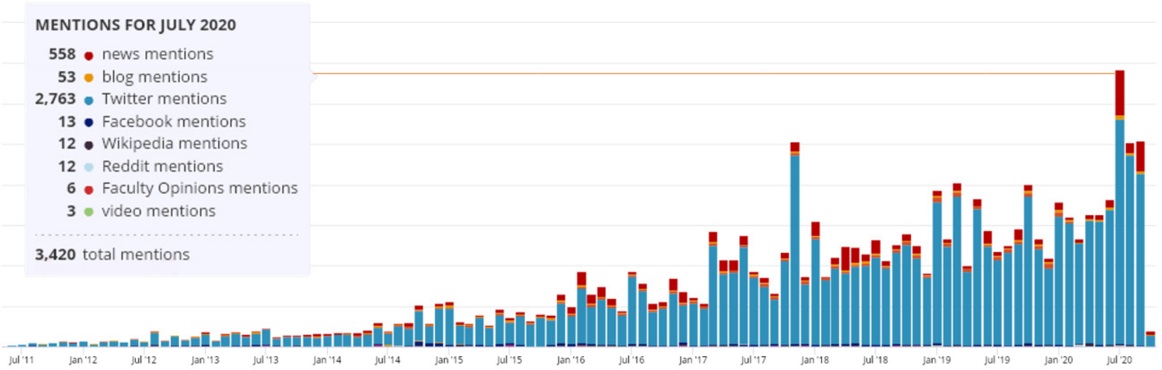


Figure 8-2: Timeline of Altmetric attention since 2011. Source Altmetric explorer.

Altmetrics scores research outputs and gives them a score based on their attention performance in the news and online. An analysis of Diamond research output shows **that 637 publications are in the top 5% of all research outputs scored by Altmetric**, this is around 8% of the tracked research output with a further 1,780 in the top 25%. Altmetric does not assess the quality of the science but shows that the research at Diamond is widely talked about and has received extensive coverage in the media.

A few articles (5) have been attributed a very hight attention score ranging from 1,252 to 2,420. Each of those articles have been mentioned in over 100 news stories (136 news mention to 296):

Characterization and engineering of a two-enzyme system for plastics...
Article in **Proceedings of the National Academy of Sciences of the United States of America**, September 2020
296 news mentions

Characterization and engineering of a plastic-degrading aromatic polyesterase
Article in **Proceedings of the National Academy of Sciences of the United States of America**, April 2018
268 news mentions

Neutralizing nanobodies bind SARS-CoV-2 spike RBD and block interaction with...
Article in **Nature Structural & Molecular Biology**, July 2020
199 news mentions

The molecular basis of thioalcohol production in human body odour
Article in **Scientific Reports**, July 2020
195 news mentions

Fragment-derived inhibitors of human N-myristoyltransferase block capsid...
Article in **Nature Chemistry**, May 2018
142 news mentions

8.4. Societal outcomes

8.4.1. Public engagements outcomes

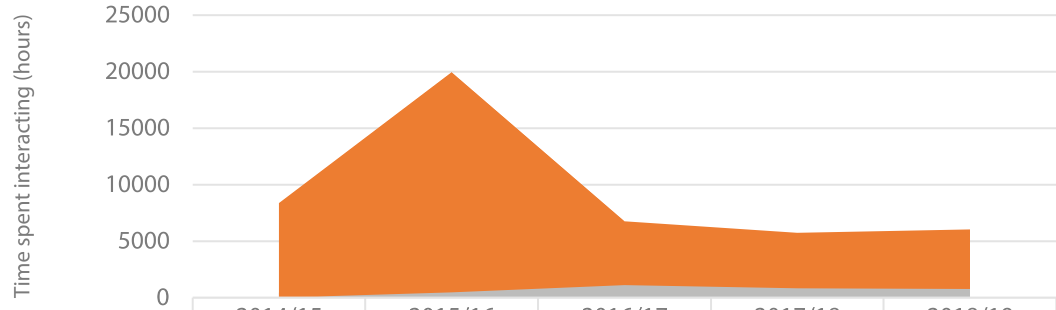
The outputs data gives little indication of the depth and quality of interaction. It is difficult to judge the impact of interactions on individuals, but it is not unreasonable to suggest that the longer and deeper the **direct exposure to STEM** professionals, the **greater the impact**. The resulting interactions created by the engagement events have been broken down by the following interaction levels:

- Low interaction level – a short conversation or talk, with limited levels of interaction with the Diamond facility. For example, a short lecture or a conversation at external venues i.e. festivals/ careers talks
- Medium interaction level – An extensive external activity or, more typically, a visit to the facility, usually involving a talk and a tour of the synchrotron
- High interaction level – An activity that takes place over several days, for example a teacher training course or work experience placement

Unsurprisingly, at an event with low level interactions there are more interactions. It may be useful to consider the time spent on each type of interaction as an indication of the overall impact that is being made. For example, talking to one person for 2 hours could be considered equivalent to talking to 12 people for ten minutes[26].

This is based on:

- A low level interaction taking 0.1 hours (6 minutes)
- A mid-level interaction taking 2 hours
- A high level interaction taking 30 hours



	2014/15	2015/16	2016/17	2017/18	2018/19
low level interaction	440	360	1000	662	302
mid level interaction	8362	19952	6750	5746	6036
high level interaction	0	480	1110	840	780

Table 5: Comparison of hours of interaction by impact type. The mid-level interactions are notably higher than average in 2015/16 due to a large public open day

Finally, Diamond has so far welcomed **124 secondary school students** for a week of work experience. Although we have very limited data on the longitudinal effects that engagement has on our visitors, every year Diamond sends a short survey to previous secondary school work experience students to build a view of their progress and how Diamond may have helped their path.

In October 2019, this survey was sent to the 89 previous students, 36 responded with the following:

- 7 were studying STEM subjects at Sixth form
- 28 were studying STEM subjects at undergraduate level
- One was studying non-STEM subjects at 6th form
- One was studying Business at undergraduate level

26 Note: time is measured as the interaction time 'received' by the visitor i.e. one person giving a one-hour tour to six visitors is 6 hours of interaction.

- 36 of the students said their experience at Diamond has generally helped them
- 1 student said they were not sure if their experience at Diamond had helped them

Diamond seemed to have helped in many ways, including **building confidence** and **boosting their CV**, with a significant number of them indicating that the week had helped **inform decisions** on further **education** and their **choice of career**.

8.4.2. Training and workshops activities outcome

Internationally recognised facilities like Diamond help drive the knowledge and skills base for the UK. Diamond invests in its staff and user community to harness the analytical capabilities on offer. In this process, Diamond trains and shares knowledge with students, supports industry and academia to best answer some of the most challenging scientific questions of our time.

In its strategy, Diamond identified the need to champion the importance of STEM skills at all levels and created a robust programme of scientific and technical engagement ranging from training through to subject-based workshops and international conferences. As demonstrated in the outputs, the training alone results in the consolidation of STEM skills through a wide cross section of higher education students.

Although this is not yet quantifiable as part of this study, Diamond does encourage long-term careers in STEM. Some evidence of this can only be found in student feedback gathered after each of the interactions with Diamond. For Year in Industry students, feedback is captured in the form of a presentation of outcomes from their project. Some of the latest feedback confirms some of the outcomes above in a qualitative way.

> *The Year in Industry has been invaluable to my development both technically and professionally"*

> *Uni taught a lot of theory but learnt practical skills as part of the placement"*

> *All skills learnt at Diamond will translate directly to final year project"*

> *Having the practical skills & software knowledge, having that on my CV, will definitely show that I've gone outside of the university theory and I have applied it in (practical) experience and that's really important with my employability."*

> *I think it's (the Year in Industry) really increased my confidence in this area and in doing science in general. It's just been really invaluable in terms of expanding my horizons. Yeah – it's been a lot of fun"*

8.4.3. Student engagement outcome

Students in higher education are an important audience for Diamond. As part of its strategy, it set out to attract and support the very best research groups in universities and institutes. Diamond trains and inspires scientific talents, as demonstrated by the Technopolis academic survey, which found that nearly all of the **academic users** surveyed (94% of 321) said that their use of **Diamond had been beneficial for their national or international reputation**. Most users also reported impacts on the international networks and reputation of their wider research group, as well as on the attractiveness of the group to other researchers and students. Most also indicated (more generally) that **the existence of Diamond was very important or critical for the attractiveness of the UK as a place to conduct research**.

With **at least 2,698** of its user community being **students or early careers**, Diamond plays a key part in encouraging long-term STEM careers and inspiring others into the importance of STEM skills for the UK's societal and economic challenges.

8.4.4. Press and media outcome

Diamond embedded a culture of engagement at the heart of the facility. This meant that maximising the impact of STEM subjects by ensuring they are properly, and where possible, accurately reported in the media was critical to its activities.

Diamond has achieved an awareness of new research addressing the global challenges & the UK's societal needs through its widespread social media and press coverage.

As a majority of the investment made in Diamond comes from the UK Government and ultimately the taxpayers, the exposure achieved through the press and social media work does feed into a strong position of transparency and accountability for the money invested so far, in line with Diamond's strategic goals to demonstrate value for money and long-term impact of the work it carries out.

8.5. Societal impacts

8.5.1. Public engagement

The nature of public engagement makes it very difficult to directly measure its impact on participants. For example, it is virtually impossible to inextricably link a one-off intervention with an eight-year-old child to their decision to pursue a career in STEM subjects, nor is it feasible to assess how a visit from a general interest group will impact on their attitudes to Diamond, or science in general. However, there are many good rationales for carrying out public engagement and any type of engagement is likely to result in participants having a greater understanding that will impact on their future attitudes and decisions.[27]

One of Diamond's key goals is to increase the uptake of careers in STEM; it is yet again difficult to map the impact of Diamond's engagement activities directly on the goal. However, studies have been carried out to test the effectiveness of engagement activities. One such study, the Aspires project, was carried out recently by Kings College London[28].

One of the outcomes of the report was the idea of '**Science Capital'**, which links the exposure and knowledge of a person to STEM with their attitudes towards it and the likelihood of them pursuing a career in STEM[29].

As advocated in the study, what this idea suggests is that the engagement of people with science has a positive impact on them and is more likely to make them think that science is 'for them', both in terms of a career and more generally something they can positively associate with. Flowing from this, there are many societal impacts from the engagement work at Diamond, including:

- Increased 'science capital'
- Increased trust in the work of Diamond (and STEM in general)
- Increased awareness of STEM careers and capabilities
- Improved skills in students, staff and public
- Greater public awareness of UK science and the benefits that it brings to society
- Demonstrable accountability in the spending of public money

These social benefits are seen not only by the directly engaged, but also by secondary and tertiary contacts; students talking to parents, teachers communicating to students etc.

Based on the events delivered at Diamond over the past 5 years these benefits can be summarised as:

- Over **50,000** individuals via direct communication
- Over **50,000** hours of interaction
- **236** different engagement events
- Over **200** different schools visiting

27 https://www.publicengagement.ac.uk/about-engagement/why-does-public-engagement-matter
28 https://www.ucl.ac.uk/ioe/departments-and-centres/departments/education-practice-and-society/aspires-2
29 https://www.youtube.com/watch?reload=9&v=A0t70bwPD6Y

- Nearly **100** high impact work experience/summer school students

Measuring the direct impact on participants of public engagement is extremely difficult as it forms part of a collective experience. In turn, estimating the economic aspects of this impact are even more complex; it is comparable to trying to measure the economic impact of individual lectures in an entire university degree course. Consequently, any financial figure produced would be of very limited use and is not generally attempted[30].

However, there are numerous reports that show the **positive economic effects** of both **STEM skills training** and **engagement**[31], and also the positive socio-economic effects on diversity and inclusion[32]. Between 2014-19, Diamond directly communicated with over 50,000 school students and members of the general public exposing them to the work we carry out and the associated careers in STEM. In 2014, on average an employee in the engineering sector contributed around £22,600 more per annum to GDP than the average UK employee[33]. Over a 5-year period, 50,000 engineers contribute around an extra £5.**65 billion to UK GDP** compared with the contribution from the same number of staff across all sectors. Even the **smallest contribution made** to this by our engagement work is **significant**.

8.5.2. Academic

Academic users were asked whether they believe that their use of Diamond has helped to deliver **impacts in a range of societal areas and sectors**. Around half of the respondents reported at least one of the areas of impact listed. This included a third that said that their use of Diamond had helped deliver impacts in the area of health, demographic change and wellbeing. A further 25% reported contributions in relation to creating secure, clean and efficient energy.

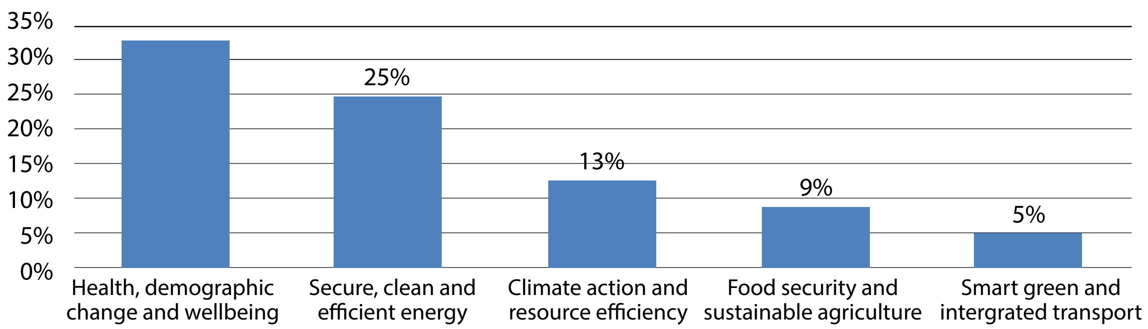


Table 6: Proportion of academic users reporting societal impacts. Academic survey (n=300)

Respondents were asked if they could point to **one concrete example** of a social or societal impact that has resulted (at least in part) from their use of Diamond. They were asked to briefly outline the impact, as well as explain the contribution of Diamond and their research to this.

Many respondents could point to the *potential* societal benefit of their research (and new knowledge and understanding gained) – either in very general terms or more specifically. However, in nearly all of these cases it was either too early to point to a concrete example (further research required, results not yet taken up in practice, etc.) or any impact was too indirect to be known (e.g. research has fed into a wider body of current knowledge). There were, however, a small number of respondents who were able to provide examples of realised societal benefits associated with their work at Diamond.

Nearly all of the **academic users** surveyed (94% of 321) said that their use of **Diamond had been beneficial for their national or international reputation**. Most users also reported impacts on the international networks and reputation of their wider research group, as well as on the attractiveness of the group to other researchers and students. Most also indicated (more generally) that **the existence of Diamond was very important or critical for the attractiveness of the UK as a place to conduct research**.

Just **over half of academic users** reported that their use of **Diamond had been very important or critical to their subsequent ability to access grant funding** (the academic case studies alone include examples of Diamond-based research serving as the foundation for further grants from Innovate UK, EPSRC, BBSRC, the Energy Technology Partnership (ETP), Advanced Propulsion Centre (APC), the Wellcome Trust and the Department for Business, Energy & Industrial Strategy (BEIS). The impact on attracting industry contracts was less widespread, but nearly half of academic users still claimed that there had been some benefit. Again, the academic case studies provide some examples, e.g. in relation to nuclear decommissioning, Alzheimer's disease and metallic implants.

8.5.3. Monetisation of training and workshops activities

There were 181 specific training events held between 2013 to 20 (Table 4), involving over 430 training days. Events included training on beamlines, data processing, software and sample environments. Across these 181 events there were 7,668 external attendees who received 19,191 days of training collectively. Nearly half of these days (8,347) are accounted for by PhD students.

The cost of a commercially available course offering similar content (€575 for a one-day 'advanced techniques of synchrotron radiation' course, run by the Soleil synchrotron[34]) can be used to estimate the total value of training received (for free) through Diamond. Following this methodology, we estimate that **the value of 19,191 days** of training across **7,668 attendees** in the past five years has been £**8.8 million** (11m€)[35].

30 Impact report for STEM Learning, the national organisation to support STEM learning funded by BEIS, DfE, UKRI, Gatsby and Wellcome https://www.stem.org.uk/impact-and-evaluation/impact

31 https://publications.parliament.uk/pa/cm201719/cmselect/cmpubacc/691/691.pdf

32 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863502/Employers_Toolkit.pdf

33 https://www.engineeringuk.com/media/1323/jan-2015-cebr-the-contribution-of-engineering-to-the-uk-economy-the-multiplier-impacts.pdf.

34 The price used is for non-members. The course programme includes: techniques and methods; preparation and handling of samples in different environments; X-ray absorption spectroscopy studies of various materials; spectroscopic analysis of materials; imaging of materials at different scales; diffraction; and the acquisition and processing of data on a beamline

35 Average exchange rate for 2013-2020 of 0.0797 calculated from the data available from the Bank of England https://www.bankofengland.co.uk/boeapps/database/fromshowcolumns.asp?Travel=NIxRSxSUx&FromSeries=1&ToSeries=50&DAT=RNG&FD=1&FM=Jan&FY=2013&TD=1&TM=Apr&TY=2020&FNY=&CSVF=TT&html.x=120&html.y=28&C=C8J&Filter=N

9. Economic impact

9.1. Economic input

As part of their strategy, Diamond has actively sought to maximise its impact though the breadth of their activities. Already we mentioned Diamond has achieved a high level of engagement with industry, developed an attractive offer drawing additional investment to the Harwell Campus, and has participated in many collaborations and grants nationally and on a European and international level. Once again, the inputs for the economic impact assessment are the same with an investment of £796.2 million with over 750 staff supporting a wide-ranging user community.

9.2. Economic activities

It is clear that Diamond has a direct economic impact essentially resulting from: the procurement of goods and services and the employment of staff and contractors. On average, around 9,000 contracts are placed by Diamond each year, with a total value of ~£40 million. Around two-thirds of its **suppliers** are UK-based, and these account for over two-thirds of expenditure. Currently, there are 434 suppliers on the procurement database. Since its creation, Diamond has issued non-construction contracts worth over £210 million, providing a range of suppliers with additional revenue and creating new employment to service these contracts.

As mentioned earlier in the report, the investment for Diamond was initiated over the three phases of capital allocation over a period of 17 years and has totalled £493 million[36] (£264.1 million for Phase I, £124 million for Phase II and £105.6 million for Phase III). Diamond's **annual expenditure** (including both operational and capital costs) started in 2007, grew in line with the development of the facility and has now reached around £85 million[37]. The overall cost of Diamond, comprising the capital investment and operational cost from the creation of the organisation until today is around £1.2 **billion**.

It also employs over 750 staff, the majority of whom are scientists, technicians and engineers, and professional staff. We estimate that through its operational expenditure **Diamond generates £84.1 million in *gross* economic impact to the UK each year**. This is based on the direct impact arising from paying salaries to Diamond employees, the induced impact on UK economic activity generated by these employees spending their incomes, and the indirect impact on economic activity through Diamond's purchase of goods and services from UK suppliers. Accounting for leakage (benefits outside the UK) and deadweight (expenditure that would have happened anyway), we further estimate that Diamond's operational expenditure generates **£3.6 million in *net* economic impact to the UK each year**.

Companies involved in **drug discovery** are heavy users of synchrotrons globally and it is thought likely that every recent drug developed and placed on the market would have been through a synchrotron at some point. It is important to note that there are around 50 synchrotron light source facilities currently in operation worldwide[38]. It has to be noted that the pharmaceutical sector is estimated overall to be worth $1,250 billion per year[39], hence structural information will have impact on R&D performance of this sector.

9.3. Economic output

For its academic users, the economic impact lays in the 941 publications with patent citations, where 1 in 10 publications is linked to a patent. This means that **a total patent citation count** of **3,455** has been achieved. More than 10% of Diamond publications have been cited, which are spread across a range of fields including organic chemistry, medical science, biochemistry and the area of measuring and testing. We estimate that these patents are collectively **valued at £5.8 billion** (in 2018 prices). The exact criticality of Diamond in each case is unknown – but some proportion of this considerable sum can be 'claimed' by Diamond. In addition, 2 start-ups were identified as part of the academic user survey.

For its industrial users, reported that Diamond had a positive impact as part of the Technopolis survey with an analysis that further extrapolated that **75 have submitted or will patent application**s; **106 will have launched new products or services**; **25 have launched new start-ups**; **55 launched new processes** and **37 will have achieved new licence agreements**.

For its suppliers, it has been more challenging to map the economic impact, but the suppliers survey found that they were able to identify the following benefits: 13 new products and services; 7 new processes; 1 start-up and 2 new licences achieved.

Overall Diamond itself has outputs which can be economically beneficial as for example the **50 licences** arising out of internal innovation.

Finally, as part of the Technopolis in-depth interviews, it was clear that Diamond was perceived by interviewees as an "anchor tenant" on the Harwell Campus, thereby helping attract companies and institutes to be in its vicinity. Harwell is now one of the largest research and innovation campuses in the UK, hosting **225 organisations**, **6,000 people and £2 billion-worth of world-leading research infrastructure**[40]. It has been estimated to contribute £1 billion to the economy and, based on its success, has recently embarked upon a new ambitious expansion plan to create millions of additional square feet of working and research space.

9.4. Economic outcome

Many of the activities and outcomes link back to Diamond's strategic goals being met. Although these are broad in nature, for example, several suppliers responding to the Technopolis survey mentioned the important role that Diamond played in simply providing a regular and continuous stream of **opportunities and income**, supporting jobs and investment, and in some cases ensuring financial survival and continued existence within the UK. Diamond set out to maximise its impact and evidence is captured in this section to support this.

Industry users

Industry users were also asked to assess the extent to which their use of Diamond had had a **commercial impact on their business**. A majority of indicated some level of impact had been seen on reducing their costs, while impacts on turnover and exports were less widespread but still significant in a few cases. Most were not willing or able to quantify these impacts, but a few examples were given:

- 3 gave information on increased turnover: £100k, £750k and £2m (£950 thousand each on average)
- 6 provided data on employment: 1, 1, 2, 3, 10 and 220 jobs (40 jobs per company on average)
- 2 provided data on annual reductions in costs relating to innovation and new product development: £50 thousand and £250 thousand per annum (£150 thousand in cost savings each on average)

The case studies of industrial users similarly identified a range of examples where research conducted at Diamond had helped in the development or improvement of products, in the reduction of cost, or in the generation of additional revenue – though usually as a result of a range of developments over a period of time, and not just research at Diamond. Some of these case examples are summarised below, combined with the study team's own market analysis as to the potential commercial impacts.

Sosei Heptares - The firm specialises in clinical-stage research into novel medicines that target G protein- coupled receptors (GPCRs), a superfamily of receptors linked to a wide variety of different human diseases including diabetes, obesity, and kidney and digestive diseases. It uses Diamond at least once a month for its research into GPCRs, generating approximately 90% of its structural data

36 Financial reporting up to 2014/15 did not include VAT, later reports do include VAT this may explain the difference from other reports.
37 The complicate financial table is given in Appendix F
38 https://lightsources.org/lightsources-of-the-world/
39 https://www.statista.com/topics/1764/global-pharmaceutical-industry/
40 Harwell Campus Strategy, January 2018

there. Diamond has been **crucial** to the company being able to carry out **high profile drug discovery work**, which is feeding into the development of treatments for life-changing diseases. This has helped **enhance the company's reputation** and standing in its sector – contributing to it being acquired by a **Japanese biopharmaceutical firm in 2015 for close to $400 million**.

Infineum - The Oxfordshire-based company has conducted a variety of research at Diamond, all with a view to reducing friction in engines and improving engine performance. For instance, it conducted real-time molecular-level examinations of biofuel performance in cold temperatures (when molecules can crystalize, forming waxes that block fuel filters to the engine). Regulatory, industrial and consumer pressures (e.g. to improve fuel efficiency and environmental performance) are driving the need for substantial innovation in the automotive sector, and novel fuel additives are expected to be critical to its ability to meet these often competing demands. Infineum is one of ten prominent vendors operating in this billion-dollar global industry, and it is well positioned to benefit from predicted future growth. The company reported that **its work with Diamon**d would be **key to its continued success in developing future generations of additive systems**.

Rolls-Royce - The company has been a regular user of Diamond – both directly, and in collaboration with academic institutions. Its activities have centred around understanding the residual stress profile of the materials used in components, which has then helped the firm to demonstrate product capability and provided a better understanding the service life of products – helping to reduce repair bills. The durability issues that Rolls-Royce has experienced in recent years with its Trent 1,000 engines gives an indication of the scale of the economic benefits that might derive from it being able to carry out more comprehensive and robust testing of whole engine systems at Diamond, as a means by which to avoid or reduce unexpected in-service issues. The Trent 1,000 engine's turbine blades have been wearing out faster than expected, requiring early replacement or repair, and this has led Rolls-Royce to make provision for around £800 million in exceptional costs for the financial year 2018, to cover both the costs of the unplanned maintenance and repair work and also some level of customer compensation.

Unilever - The company has used Diamond to **test and refine** a proposed new hair care product, using the I22 beamline to examine the microstructure of the product once diluted. Having demonstrated the new product's stability and suitability, the prototype has now progressed to an "in-home trial". The benefits could provide substantial financial leverage, as leading shampoos can have global revenues in the hundreds of millions of dollars. For example, Unilever's 2017 Annual Report lists Sunsilk (including a range of shampoos) as **one of its 13 brands with global sales in excess of $1 billion**.

Lewtas Science & Technologies - The company used Diamond to develop a new (non-toxic, but still comparably malleable) **plasticiser replacement** for use in polymer-based manufacturing. It is currently working to commercialise this product, with first sales expected imminently. The current **global market for plasticisers** is valued at **US$20 billion** and is growing at around 5% a year. The potential market for a new (non-toxic) plasticiser replacement is therefore substantial.

Synergy with the UK's Government policy

The UK Government's Industrial Strategy[41] underpins the Government's economic strategy and highlights Grand Challenges to put the UK at the forefront of the industries of the future: to be a leader in the **artificial intelligence and data revolution**; to equip UK industry to be best prepared for **clean growth**; to be at the forefront world-wide in the **mobility of people, goods and services**; and to help meet the needs of **an ageing society**. Since the formal launch of the UK's Industrial Strategy, Diamond actively undertakes research and activities that underpins its delivery. Diamond is and continues to be an agent of change for 21st century global challenges.

Experiments that deliver big data

Data rates from Diamond are already approaching petabytes per month and future upgrade plans are expected to be at least an order of magnitude greater. With increased data volumes come new challenges and exciting new opportunities for data analysis to effectively extract new knowledge from the data. Modern data science techniques in deep learning and AI approaches have particular applicability in areas where, to date, human intervention has been essential for successful data analysis because analytical methods have not proven useful.

41 https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/industrial-strategy-the-grand-challenges

Delivering knowledge generation for the clean growth agenda

The completion of the Phase-III instrument programme has added 10 beamlines, which ensures that the investment in Diamond fully maximises return on the initial capital investment. Some **25% of academic respondents** to the Technopolis survey said that their work at Diamond had **made contributions in relation to creating secure, clean and efficient energy**. As an illustration of the impact of these new beamlines, and just one of many possible examples, the latest work around the plastic digesting enzyme (PETase) is the epitome of the huge impact world leading instruments can make.

Insights into how PETase is structured, and how it works, that have been garnered from Diamond's MX beamlines will be invaluable in designing a highly-efficient plastic-degrading machine for the future. Tailored PETases like those measured at Diamond could be used for large-scale industrial recycling processes and offer an innovative solution to the plastic waste problem that we desperately need.

Another example of the science undertaken at Diamond, which is contributing to the clean growth agenda, is the study of storage in metal-organic frameworks (MOFs) of toxic iodine vapour from nuclear industry operation with the aim of designing more efficient and effective capture systems. Using Diamond allowed researchers to fully determine the position of the iodine molecules for the first time within the MOF pores, which are less than 1 nm in diameter. MOFs are unique materials that present a structure of exceptional porosity. By synthesising structures of differing pore sizes, MOFs can be used to filter, trap, or transport molecules. Research into better understanding MOFs has been largely driven by the wealth of potential applications in hydrogen storage, catalysis, drug delivery, carbon capture and more that these materials may have.

A final example illustrating and amplifying how Diamond provides enabling tools for basic research is the discovery of Weyl quasiparticles. These particles are many millions of times more sensitive to magnetic changes than the materials in current computer hard drives. This means they have the potential to store vastly more information per disk. The Weyl fermions themselves can carry an electrical charge and move much faster than electrons in normal materials potentially leading to much faster electronics. The unusual arcs that connect the Weyl points also demonstrate a unique property that, if combined with other exotic materials, could make them useful for quantum computing – a technology believed by many to be the future of computing. From an industrial strategy perspective, this has opened the door for the exploration of new electronic systems that could potentially be designed to step change their energy efficiency and storage capabilities compared to current technology.

Enhancing the UK skills base

With over **80,000 visitors** already welcomed to the facility, the potential for Diamond to attract a wide range of audiences is clear. The commitment made by Diamond as part of its strategic objectives remains central to the Industrial Strategy and offers a unique opportunity to engage and inspire.

With over 80 events per year the facility is a catalyst for the Industrial Strategy's approach to strengthen skills and build on delivering a world-class education system (secondary, technical and higher education) as well as ensuring that the UK remains at the forefront of science and technology. World-class skills offered by Diamond are one of the most important ways in which the UK can maintain its position as one of the major knowledge economies in the world. The **size of its user community** has reached some **14,000** and **at least 2,698 are currently students** or **early career researchers**. As result, Diamond is a leading training provider delivering high quality experimental tools and support to over 5,189 early career researchers and students as of 2020.[42]

42 Data source: The Diamond's User Administration System, 2020.

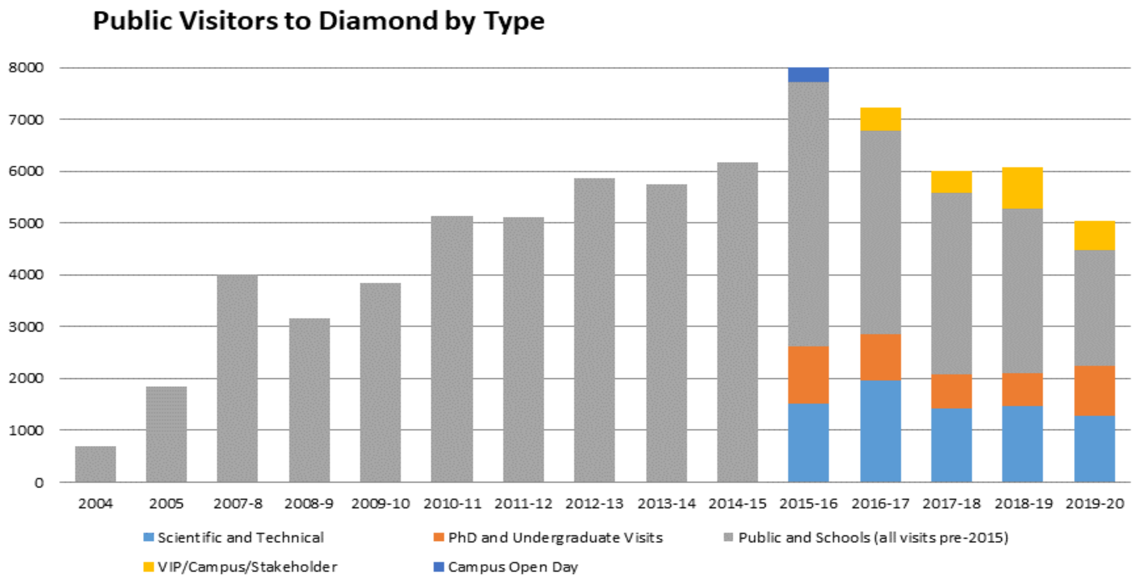


Figure 9-1: Visitors by type outside beamtime usage. March 2020 saw a cut due to Covid outbreak to the visitors programme hence the 1000 decrease as March is a critical moth for visits, events and training. Data until 2015 was not broken by category.

Diamond's **contribution to the skills agenda** was also widely acknowledged in the Technopolis academic survey, where **the majority of academic respondents** claimed that Diamond had a **significant impact on knowledge and skills**. **Two thirds of respondents** reported **significant impact on the capacity of their research group** and international reputation, contributing to the **attractiveness of their group to other researchers and students**. For example, one comment provided was that "the opportunity to carry out experiments at Diamond had been a major attraction for prospective PhD, masters or undergraduate students looking to join our research group". **Most academic users** (92% of 302) also indicated more generally that **the existence of Diamond was very important / critical for the attractiveness of the UK as a place to conduct research** (i.e. as a means to attract / retain talent).

Science helping an ageing society

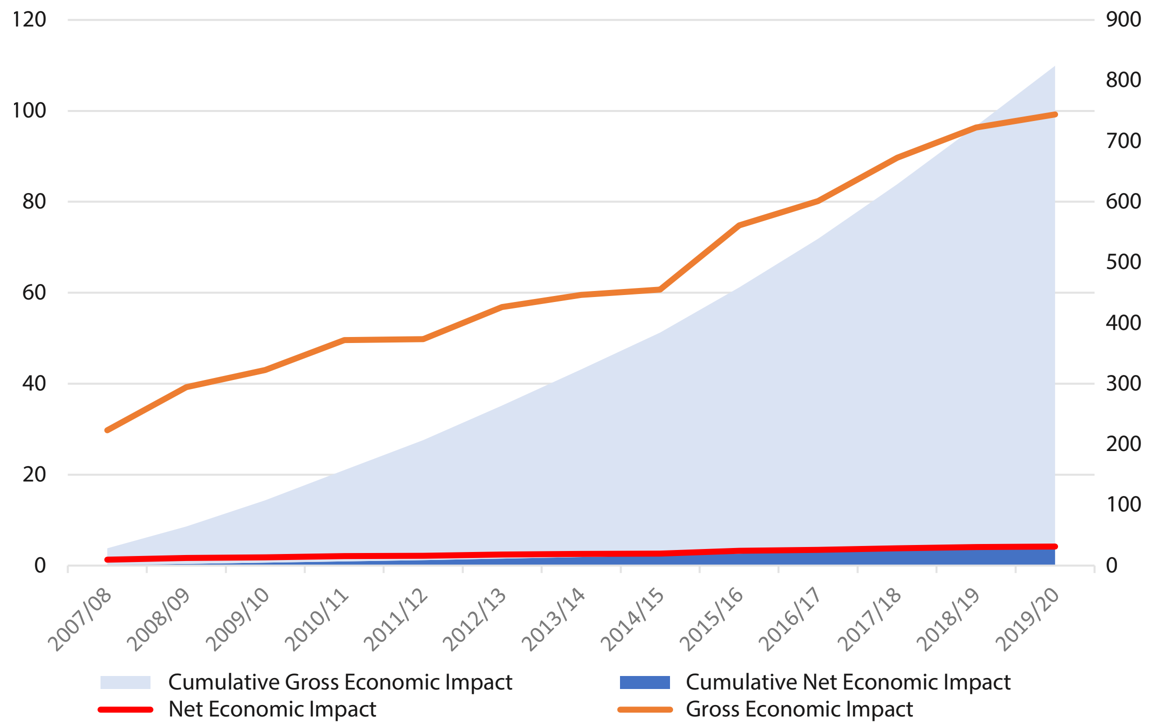
A third of academic respondents said that their **use of Diamond** had helped deliver **impacts** in the area of **health and wellbeing.** An ageing population presents increasingly urgent challenges that are driving research at Diamond into new biomaterials from heart valves to prosthetics. In addition, infectious diseases are the second leading cause of death in the world after cardiovascular diseases. Much has been achieved in the past decade in terms of prevention and control, but as the Covid-19 outbreak has taught us, it remains clear that the swift and effective design of therapeutic agents will play a critical role in disease control. Diamond has been involved in rapid response programmes of research to better understand basic processes behind pathogenic processes linked to the virus causing Covid-19[43] with a view to identify therapies.

Recent successes by researchers include better understanding of antibiotic resistance[44], a range of therapeutic drugs for breast cancer[45], new materials for prosthetics[46] and pushed the boundaries of 3D bioimaging down to the cellular level with a view to improve medical diagnostics[47]

43 Science in Parliament article, October 2020.
44 Https://www.diamond.ac.uk/Home/Corporate-Literature/Lit-reviews/antibiotics.html
45 […] A Potent and Orally Bioavailable Selective Oestrogen Receptor Down regulator and Antagonist; DOI: 10.1021/acs.jmedchem.5b00984
46 The chemical form of metallic debris in tissues surrounding metal-on-metal hips with unexplained failure; DOI: 10.1016/j.actbio.2010.06.006
47 https://www.diamond.ac.uk/Home/Corporate-Literature/Annual-Review/Review2019/Science-Groups/Imaging-and-Microscopy-Group/Maximising-information-from-precious-biological-samples--Combining-3D-X-ray-imaging-with-traditional-2D-histology.html

9.5. Impact

We estimate that through its operational expenditure **Diamond has been generating over £80 million in *gross* economic impact to the UK each year in the past few year**. This is based on the direct impact arising from paying salaries to Diamond employees, the induced impact on UK economic activity generated by these employees spending their incomes, and the indirect impact on economic activity through Diamond's purchase of goods and services from UK suppliers, Accounting for leakage (benefits outside the UK)[48] and deadweight (expenditure that would have happened anyway)[49], **we estimate that Diamond's operational expenditure generated £35.5 million in *net* economic impact to the UK since 2007.**



Many suppliers have also seen wider commercial benefits. The Hexapod provides a good example. Diamond developed this support system for mirrors in collaboration with FMB-Oxford, before four were installed on site. Having demonstrated the success of this new product, FMB-Oxford has gone on to sell a further ~20 systems, mostly to other synchrotrons, generating sales in excess of£2 million.

48 We estimate that ~32% of Diamond's indirect impact falls outside the UK, based on Diamond's contracts and tenders database showing that (where known) 68% of total expenditure (2003-17) was allocated to suppliers based within the UK. All Diamond staff are resident in the UK (i.e. level of leakage outside the UK is equal to 0).
49 We estimate that ~95% of Diamond's operational expenditure is based on UK grant income (predominantly from STFC and the Wellcome Trust). In the absence of Diamond, these funds would likely be allocated elsewhere and therefore still be generating similar economic benefit through expenditure on staff and supplies. The 5% remaining relates to other commercial or international income to Diamond, which would be less likely to exist without the facility.

10.Conclusions – future assessments

Based on the experience and learning from undertaking this study, Technopolis has put forward a proposal for an evaluation framework that could be used as the basis for tracking the facility's performance in the future and monitor impact. This is a revised and updated version of the framework deployed for the current study and is designed to support future evaluations by ensuring there is a more wide-ranging and complete record of achievements across each of three principal impact pathways (knowledge, skills, innovation).

The framework includes a series of suggested metrics (indicators, methods and sources), designed to allow the facility to more clearly understand and demonstrate the extent to which it is supporting beneficial outcomes. Most of the evidence relating to inputs and outputs will be derived from Diamond itself, via established databases and reporting, while the evidence for computing outcomes and impacts will comprise a mix of internal (Diamond) and external (future evaluators) data collection exercises.

It should be noted that the initial budget for this study did not allow for the full scoping of negative impact, but this will be taken into consideration for future studies.The framework is designed to allow a high degree of quantification across all impact pathways, including monetisation of benefits, where possible. The current study explored several options to monetise impact, each of which experienced difficulties and limitations. We document these methods and the lessons learned, as it could serve to inform future evaluations.

Some of the suggested sources of evidence already exist, while others are new, and the report sets out recommendations for possible improvements, extensions and additions to current monitoring and evaluation activities to help address any gaps. This includes recommendations for additional questions within beam time application and user surveys, a more-standardised biennial bibliometric exercise, additional social-/media analysis, and an increase in the numbers of case studies developed.

The framework also points to the need for several new data collection activities, including suggestions for new (periodical) surveys (e.g. of Diamond-related start-ups and suppliers, as well as unsuccessful applicants for beamtime), a follow-up survey with past users and new questionnaires to collect feedback from attendees of Diamond's various training and public outreach activities.

The intention of this framework is to improve ongoing monitoring and data collection activities, such that future evaluation efforts have a better evidence base with which to assess the wide-ranging impacts of Diamond. The proposed measures do include data and case studies that will explore the critical nature of Diamond's contributions and counterfactual. However, the final challenge of determining the net benefits to the UK must still fall to the external evaluators, who will be expected to sense check the various data gathered and collated by Diamond and to run separate exercises of their own to robustly test the additionality of Diamond's activities. However, the proposed Diamond-II upgrade programme provides a good opportunity to explore what researchers will do in the absence of the facility. This could be set up as a good natural experiment to explore the counterfactual, although we appreciate that Diamond is already working hard to minimise disruption to its user base, e.g. through discussions with other facilities regarding access for its users. Based on the Diamond Logic Model used for this study, Diamond has drawn a new model for the Diamond-II upgrade programme.

Notes

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Diamond Light Source Ltd
Harwell Science & Innovation Campus
Didcot, Oxfordshire OX11 0DE
Tel: +44 (0)1235 778 639
Fax: +44 (0)1235 778 499
www.diamond.ac.uk

wellcome

UKRI Science and Technology Facilities Council