Institution: University of Sheffield
Unit of Assessment: B-12 Engineering
1. Unit context and structure, research and impact strategy

1.1 Overview

As engineers, our overarching goal is to make the world a better place. We are committed to undertaking excellent fundamental research and creating discipline-leading innovations to address key global socio-economic challenges. It is ingrained in our research culture that discoveries drive innovation, and innovation drives discoveries. This research lifecycle is fostered by a vibrant, diverse and inclusive multidisciplinary environment. To connect and bring together our academic departments and translational centres, we have defined four challenge-driven research themes, shaped by societal grand challenges:

- **Energy** with a mission to create low/zero-carbon technologies and systems and to address the energy security, sustainability, and affordability challenges of the 21st century.
- **Infrastructure and Environment** aims to deliver innovative transdisciplinary research that enables sustainability, and resilience in response to demographic and climate change.
- **Manufacturing** works with regional, national, and international partners to meet global competitiveness and sustainability challenges via fundamental discovery in processes and materials.
- **Engineering for Life** has the vision to drive innovation in healthcare for an ageing population, address healthcare disparities and foster the revolution in personalised healthcare.

Our strategy has sought to invest in research facilities and recruit staff and PGRs to deliver our ambitions, underpinned by strong growth in external grant funding. In the assessment period, we have become one of the largest engineering research communities in the UK, with over 1,900 academics, researchers, technicians and PGRs. As well as our four challenge-driven themes, we provide numerous mechanisms to enable our diverse research community to identify opportunities for 'bottom-up' research areas to grow and be productive.

Our six academic departments, together with the Advanced Manufacturing Group (AMG), our sector-leading translational research flagship, have delivered on our REF2014 strategic objectives of expansion, excellence and reach, and we have experienced 7 years of unprecedented growth and success.

Highlights include:

- **£623M in external research income**. HESA data places us 2nd in the UK over the period, and 1st in 2017/18 with £118M. This includes a 110% increase in annual RCUK funding.
- Significant internal investment alongside external grants (EPSRC, ERDF, BEIS) to create **17,760 m^2 of new research and translational facilities**.
- More than **150% increase in the rate of open access publication**, ensuring wide-scale dissemination of our discoveries and impacts across our disciplines.

- An **increase of 51% in academic and research staff**, supported by a **74% increase in technical staff** to ensure excellent support in our new research facilities.
- **Annual Doctoral awards increased by 44%.** Creation of an Engineering Graduate School has enhanced PGR experience and we have either built or refurbished 70% of PGR accommodation (5,932 m^2).
- **New strategic partnerships** with global industry leaders (e.g. Airbus, GKN Aerospace, McLaren, [text removed for publication]), are central to our research and innovation agenda.
- We have **impacted on growth in the region and nationally** via leading SME engagement and knowledge exchange programmes such as "Fit for Nuclear" - involving 757 SMEs and creating and safeguarding 1100 UK jobs.
- Our impact and innovation pipeline covers all thematic areas and underpins over **£4.5bn of economic value**, as evidenced by our 11 impact case studies.

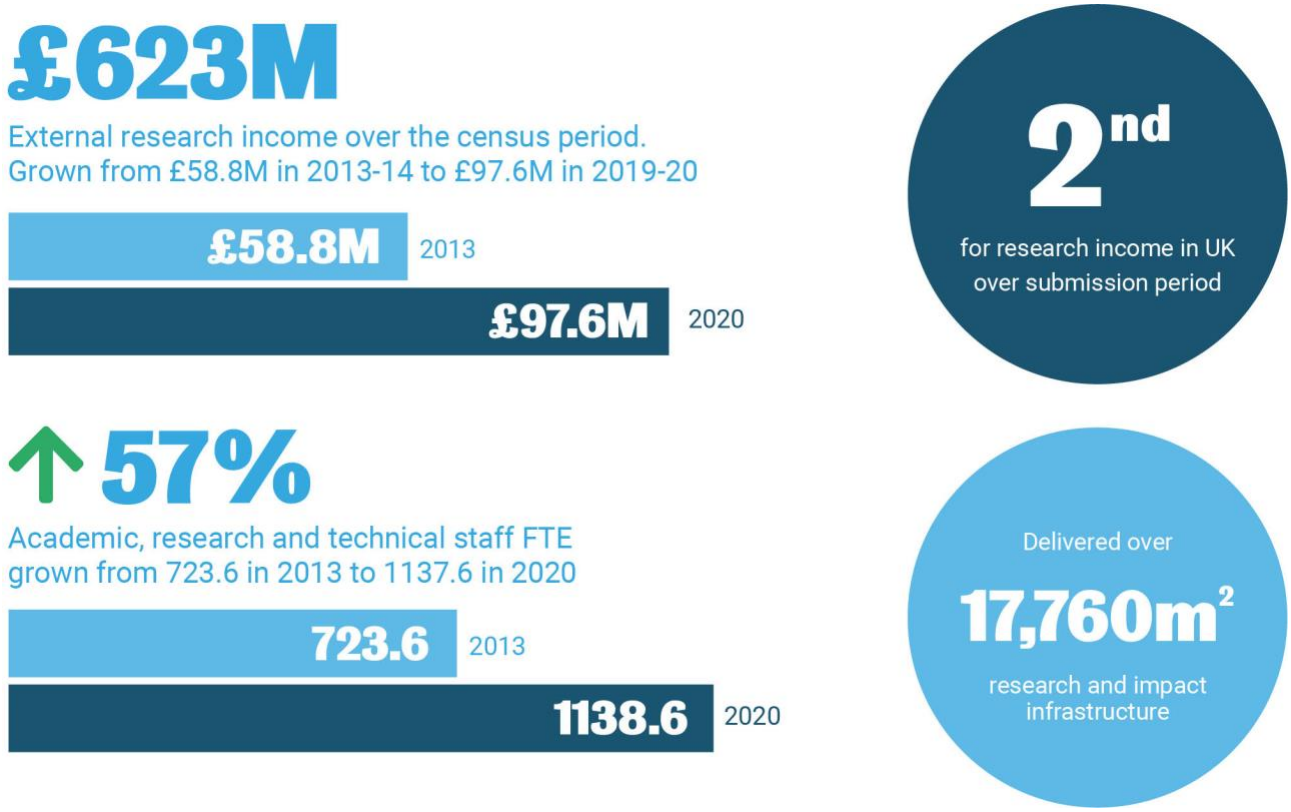

Figure 1.1 – Key growth highlights

1.2 Unit structure

Our unit structure efficiently and effectively facilitates a joined-up approach to our research and innovation activities, exploiting the synergies between the six academic departments and the two major translational centres under the AMG (Figure 1.2): leadership structures, and the focus on challenge-driven research themes, enable coordinated top-down strategy, decision making and planning; departments, research groups and communities contribute to the creation of bottom-up drivers for research; and, our translational research centres and facilities act as a catalyst for industry engagement and impact.

Figure 1.2 Major components of Sheffield's Engineering submission

Leadership structures. The six academic departments sit within the Faculty of Engineering, led by Head of Faculty and University Vice-President (Hounslow). Long-term vision and strategy for the Faculty, as well as investment decisions, are overseen by the Faculty Executive Board (FEB). FEB provides a strategic framework within which departments can define aligned local strategies and objectives. This structure is a crucial mechanism to efficiently coordinate and support our broad research base. This structure is further facilitated by a research directors committee (Faculty Research and Innovation Committee), chaired by the Faculty Director for Research and Innovation (FDRI, Panoutsos). This cascade governance structure ensures a clear and cohesive framework for decision making, strategy and planning across Engineering.

Both the University Executive Board (UEB) and University Research and Innovation Committee (RIC) include representation from the Faculty of Engineering and the AMG, giving both a leadership voice in thinking and strategy development (REF5a). We facilitate coordination between our six academic departments and the AMG through the Manufacturing Research Board (Section 1.4). This is a key instrument for further strategy and operational alignment. Other key unit

structures are our *translational research centres and research facilities* (Section 3.3), and our interconnected *research and innovation support structures* (Section 1.4).

1.3 Research themes, strategy, and progress towards REF2014 objectives

Early in this assessment period we committed to an ambitious programme of targeted growth, with the aim of further strengthening our areas of excellence, extending our reach and impact, and investing in research facilities in areas of strategic importance. We established four strategic objectives to enhance our research environment:

- Fostering a culture of interdisciplinarity.
- Investing in challenge-driven research excellence.
- Promoting research collaborations and diversity.
- Nurturing and sustaining impactful research and partnerships.

In Figure 1.3 we outline REF2014-specific objectives and reflect on progress with reference to our six REF2014 2014 submissions.

	REF2014 plans	Evidence of achievement 2013-2020
REF 2014 – UoA12A Department of Mechanical Engineering and Advanced Manufacturing	• Income growth – focus on large funding opportunities in manufacturing, bioengineering, dynamics, acoustics and energy. • Improve infrastructure of all Departmental laboratories • AMRC – construction of Factory2050	• Over 90% growth from REF2014. Major funding awards in Energy, Dynamics, Acoustics, Bioengineering and Manufacturing, see Sec. 3.2 • Main Engineering Building refurbished including laboratories – see Sec. 3.3.2. New major laboratories: TERC/PACT – Energy; LVV – Dynamics see Sec. 3.3.1. • Factory 2050 completed + 6 other major projects – see Sec. 3.3.1.
REF2014 – UoA12B Department of Chemical and Biological Engineering	• Grow research income, use funding to couple research with innovation to solve societal challenges, focus on large grants. • Set up Advanced Biomanufacturing Centre (ABC) • Infrastructure: Engineering Graduate School (EGS)/ Engineering Teaching Building (ETB) to enable enhanced laboratory and PGR space	• Annual research income grew by 170%. Large grants in energy storage, plastic reuse and green manufacturing addressed societal challenges, see Sec. 1.3.1 & 3.2. • ABC launches in 2014 generated over £12M much of it from industry. Academic growth by 3 to 9. See Sec 1.3.3 • EGS and ETB completed. New high quality space for 75 PGRs, 5 PDRAs and 6 academics. ETB hosts the Diamond Pilot Plant, see Sec. 3.3.2
REF2014 – UoA13B Department of Electronic and Electrical Engineering	• Expand semi-conductor research activities beyond fabrication expertise • Expand wireless networks activities • Electrical Motors and Drive Group to interface with energy generation and storage technology	• Extend to wide gap GaN and power FETs; InAs and GaSb infrared devices; quantum dot emitters; and hybrid organic optoelectronics for imaging, environmental and lithography applications. Income rose to £8.8M • Focus on energy efficiency in wireless communication systems and networks: over 100% income growth, acquired National Millimetre Measurement Facility see Sec. 3.3.2. • Energy generation and storage focus. Signifi cant EPSRC grant capture (>£14.4M), plus CDT. See Sec. 1.3.1, 3.2 & 4.5.

Figure 1.3 Achievement against REF2014 plans

The following sections outline our new strategy and provide evidence for how our four objectives have underpinned research excellence and growth across all our challenge-driven research themes. For each theme (Sections 1.3.1 – 1.3.5) we detail vision, strategy, support mechanisms, and progress towards our objectives since REF2014 as well as future strategy and plans.

1.3.1 Research Theme: Energy

Energy research spanned multiple REF2014 submissions (UoAs 12-15). We have delivered on our aim to coalesce our critical mass through a strategic cross-disciplinary approach, as well as through co-location, new infrastructure and fostering new stakeholder relationships. Mechanisms to deliver this strategy include investing in new academic leadership, forming a cross-disciplinary institute that is now one of the University's four Flagship Research Institutes, grown our research funding portfolio and built and equipped a £21M Translational Energy Research Centre (TERC) funded by BEIS, ERDF, and University investment. A commitment to train the new generation of engineers led to partnering in six energy-related EPSRC CDTs. As a result, our key research areas in this theme have flourished.

Combustion and Carbon focuses on controlling the emissions of alternative and new low carbon fuels. TERC hosts 24 pilot-scale test rigs, including state-of-the-art equipment unique in academia. We host the EPSRC UK Carbon Capture and Storage Research Centre (£1.9M) and the Advanced CO_2 Capture Technology Pilot Plant. Our work (e.g. EPSRC programme grant 2012-2017, £2.4M)

has had multiple policy impacts: membership of the DECC Scientific Advisory Group, G20, EU, Royal Society policy briefing documents.

Wind Energy Our strategic partnership with Siemens-Gamesa has led to co-location of researchers from industry in our joint Siemens-Gamesa Renewable Energy Research Centre. Zhu leads this and holds an RAEng/Siemens Research Chair (2014-2023). We lead an EPSRC Prosperity Partnership (£2.6M), are a partner in the Offshore Renewable Energy Catapult Powertrain Research Hub (£700k), and host fellowships in structural health monitoring (Worden, EPSRC £880k; Cross, EPSRC £580k). Research has resulted in world-leading electricity generator designs for wind turbines (impact case study: *Siemens-Gamesa*), and we have discovered new approaches to wind turbine damage detection (*Renewable Energy* 168: 1249-1264), followed by a patent (WO2020161309A1).

Nuclear Energy focuses on safe immobilisation of historic radioactive Higher Activity Wastes (HAW) and our research has successfully demonstrated safe disposability based upon our research (impact case study: *HAW Management*). We host the HADES/MIDAS hub of the National Nuclear User Facility (University/DECC/EPSRC £3.75M). Strategic leadership was enabled by an RAEng/NDA Research Chair (Hyatt), supported by two early career fellowships (Corkhill, EPSRC £1.1M, Thorpe, EPSRC £401k). In thermal hydrodynamics we lead modelling studies for the BEIS Digital Reactor R&D Consortium, where we created new reactor calculation methods (*Nuclear Engineering and Design*, 355: 110318).

Energy Storage has provided leadership and involvement in significant national programmes. We are key contributors to the UK's Faraday Battery Challenge (£8.5M) and are engaged in five of the nine Faraday Institution large-consortia projects. We lead on 'next-generation cathodes' and contribute to 'prolonging battery lifetime', 'solid-state batteries', 'sodium-ion batteries', and 'electrode manufacturing' (*Nature Communications 11: 6392*). Sheffield energy storage research is highly-collaborative with chemical engineering and materials science expertise contributing to solving complex challenges as we transition to a zero-carbon future. To overcome emerging energy storage challenges, we work with major energy companies, such as EoN at our 2MW Willenhall Grid-Scale Battery Demonstrator (£4.6M).

Future Strategy. In the next period, we aim to achieve further impact in structural health monitoring, in nuclear and in low carbon technologies, such as biofuels, including fostering links with our new Sustainable Aviation Fuel Centre. Exploiting our large translational research facilities, and our leadership of the University's Energy Institute will be key. For example, via fundamental research we aspire to underpin sector-leading zero-carbon technologies, and develop the technology required to safely dispose of the UK's 140 tonne plutonium inventory, recognised as the highest hazard challenge on the Sellafield site.

1.3.2 Research Theme: Infrastructure and Environment

At the heart of our strategy are transdisciplinary collaborative communities that understand and overcome the 'wicked' problems that infrastructure poses. Our ethos is that while technical innovation is key, it is not sufficient in itself. We work to deliver integrated, systems-based, socio-technical innovation, and ensure a range of policy and practice impacts that deliver transformation. Essential to our success, and aligned with our strategic objectives for our environment, is a focus on leading cross-sector collaboration. Full-scale research facilities enable this via realistic interactions and complexity. For example, our Integrated Civil and Infrastructure Research Centre (ICAIR: £10M ERDF, UKRI and University) enables academic collaboration and industry to de-risk novel technologies.

Water engineering. We lead the largest UK-based urban water engineering research group. Our TWENTY65 EPSRC Grand Challenge consortium of six UK universities (£2.4M) epitomises our strategy. Its transdisciplinary, socio-technical approach coupled with sector wide collaboration and long-term vision are leading to substantial impact (case study: *Managing discolouration*) and discoveries (e.g. *Science of The Total Environment*, 593–594:571-580). The UKCRIC National Distributed Water Infrastructure Facility (EPSRC, £3.7M) is the latest of our suite of full-scale facilities, enabling research on pipe, ground and loading interaction never before possible. Our EPSRC programme grant, 'Pipebots', £2.6M, utilises this facility to investigate autonomous in-pipe inspection systems.

Blast and impact engineering. Highly specialised facilities at Harpur Hill enable us to lead at international level, studying blast and impact interactions at a scale and complexity not possible anywhere else in the world (*Proc. R. Soc. A.* 476: 20190791). Aligned with our strategy to invest in research leadership, we made the professorial appointment of Genevieve Langdon from the University of Cape Town, bringing world-leading capability in structural response to blast. Our end-user collaborations enable us to deliver transformation (impact case study: *Blast protection*). We have developed key collaborative partnerships in this area, e.g. an RAEng/DSTL Chair, and via our membership in the MoD national Centre of Excellence in Energetic Materials.

Systems and Infrastructure was an emerging sub-theme in REF2014 that we have developed as it aligns with our strategic objective to support excellent and impactful interdisciplinary research. We have integrated research on energy, carbon and material flows in buildings and cities, considering infrastructures as complex interconnected systems. For example, at the interface between energy systems and information systems we disseminated influential work on smart grid security (*IEEE Trans. on NNLS* 27(8):1773-1786). Key mechanisms for the success of our strategy here include leading networks and centres (Sections 3.3 and 4.1).

Communications. Our collaborative trans-disciplinary strategy saw us leading the EPSRC network CommNet II, defining the UK's roadmap for ICT research on communications and networking infrastructure; key work here includes resource allocation in spectrum-sharing (*IEEE Trans. on Communications 62(7):2366-2377),* frequency selective surfaces (DSTL, £1.24M) and energy efficient networks (EPSRC, £618k). We lead the National Millimetre Wave Measurement Facility (EPSRC, £1M) enabling us to drive the UK's research on millimetre wave components, circuits, and subsystems, including research and significant awards that put us at the forefront of 5G and 6G systems (EPSRC £853k; WAVECOMBE H2020 €577k).

Future Strategy. Strategic partnerships and large-scale translational research facilities will continue to be at the core of our plans. We will increase our focus on legacy infrastructure and harsh environments (themes emerging from our most recent research), repurposing, retrofit and sustainability; generating and translating the knowledge and understanding for the UK to accelerate its emerging status as a world leader here. Exploiting 5G/6G communication connectivity between systems (energy, healthcare) will be a strong focus. We foresee a number of interdisciplinary opportunities cutting across infrastructure (e.g. advanced manufacturing, public health and improving wellbeing).

1.3.3 Research Theme: Manufacturing

We have the largest share of EPSRC's Manufacturing the Future portfolio with £40M of live awards in 2020 (£20M in 2014), enabling multiple outputs and impacts. We made significant progress towards developing a cross-institutional approach to manufacturing research and our Manufacturing Research Board is a key mechanism to deliver our strategy.

Our strategy revolves around exploiting our world-class network of research and innovation centres, working with industry partners to jointly guide fundamental research towards knowledge exchange and impact. This includes investing in industry-scale and industry-relevant translational research infrastructure, such as pilot lines, and a strong portfolio of innovation projects. Over the assessment period, investment in infrastructure as a mechanism to support our ambition has been pivotal (Section 3.3). Deep partnerships with industry enable us to understand challenges in different sectors which ensures effective knowledge exchange through access to research strategies, co-development of technology roadmaps, co-design of facilities, and co-location of teams.

Materials processing. Leadership and collaboration are at the heart of our approach. We lead the EPSRC MAPP Hub (Manufacture using Advanced Powder Processes) and lead the national Advanced Metals Processing theme via our partnership in the Henry Royce Institute. We discover new processing and design routes (e.g. *Nature* (565):305–311). A system engineering approach brings together mechanical, materials, control, and electrical engineers to develop 'right-first-time' manufacture in challenging-to-optimise processes such as additive manufacturing. We have a substantial translational research portfolio (e.g. IUK FASTSTEP3, and DAM >£1.2M).

Advanced machining and tribology. Machining research spans many decades and underpins the creation of our Advanced Manufacturing Research Centre. In this assessment period, we have built on our strategic partnerships with numerous translational programmes (e.g. IUK SAMULET with Rolls-Royce, IUK Landing Gear of the Future with SAFRAN, IUK Gear and Actuation Manufacturing with Boeing) and delivered significant impact (Rolls-Royce and Boeing factories; impact case studies *Rolls-Royce Tribology;* and *Rolls-Royce aero-engines*). Investing in our future, we led an EPSRC IDT and a CDT in Machining Science, addressing challenges of hard-to-machine materials (composites, high strength alloys). Pivotal work includes tribo-acoustic sensors for measuring machine element contacts (*Ultrasonics* 94:364-375), supported by a £1.3M fellowship to Dwyer-Joyce.

Digital Manufacturing focuses on developing data-driven approaches for intelligent control and optimisation of manufacturing processes and operations. Our academic department devoted to control and systems engineering is unique in the UK. We have exploited this to interface state-of-the-art fundamental research in control and systems theory with advanced manufacturing through translational research programmes (e.g. IUK MIRIAM, VULCAN, AIRLIFT ~£1.73M) and interdisciplinary outputs (e.g. *IEEE Trans on IE* 66(5):3794-3803). We lead key fundamental research programmes (e.g. EPSRC DigiTwin, £1.4M). Strategic investment in leadership, and co-location have been key enablers, such as Tiwari, RAEng/Airbus Chair, leading on the Wing of Tomorrow and Wing of the Future industry programmes.

Pharmaceuticals and formulated products. In collaboration with our core stakeholders in the pharmaceutical industry who provide ~£1M research funding annually, our Advanced Biomanufacturing Centre uses multiple host cell systems, from mammalian to algae and bacteria, to make high-value lifesaving biopharmaceuticals and high-volume commodities. State-of-the-art mass spectrometry funded by BBSRC, is developing computational design platforms, derived from high throughput 'omic data, leading to influential discoveries in programmable RNA shredding (*Molecular Cell* 56(4):506-517). We are partners on the EPSRC Continuous Manufacturing and Crystallisation Hub, generating significant impact on granulation (impact case study: *[text removed for publication]*).

Future strategy. We will continue to grow our manufacturing research portfolio, partnerships, research facilities and leadership in the national manufacturing research agenda. Continuing to focus on connecting novel engineering research with manufacturing expertise within our AMG will

be key, as well as developing new research areas in national priority themes (e.g. via our leadership of the EPSRC Future Electrical Machines Manufacturing Hub). We have identified digitalisation, resource efficiency, and manufacturing resilience as key areas for growth.

1.3.4 Research Theme: Engineering for Life

Our overarching aim is to foster the revolution in personalised healthcare, responding to evolving regulatory agency requirements and contributing substantially to reducing the cost of innovation in healthcare in an ageing population. Our strategy is tailored to suit the key stakeholders in medicine and biosciences.

In-silico medicine drives the development of technologies to provide patient-specific predictions for clinical decision-making, in close collaboration with healthcare practitioners. We launched the INSIGNEO Institute for *in-silico* medicine in 2012; it is now Europe's largest research institute dedicated to the development, validation, and use of *in-silico* medical technologies. INSIGNEO brings together 153 researchers from Engineering, Medicine, Science and Sheffield Teaching Hospitals. For example, in this period, patient specific multiscale models of the musculoskeletal system have predicted the risk of bone fractures for individuals (Frontier Engineering, EPSRC >£5.5M) and led to key outputs (e.g. *Biomechanics* 73:108-118).

Biomaterials has addressed the challenge of a healthy and ageing society, through open access biomaterials microfabrication and non-invasive imaging (*Chem. Sci.*, 2014,5:879-886) for regenerative medicine (MRC £730k). Underpinning programmes include multiple EU-funded projects (~€910k SPINNER and NEURIMP) for numerical and experimental repair strategies, implantable polymeric nerve guides, and reinforced bioresorbable biomaterials. We are a partner in a new CDT for Advanced Biomedical Materials, and we have successfully translated our research into real-world impact, such as scaffolds for corneal repair (impact case study: *Saving eyesight*).

Neuroscience. We contribute to the University's Flagship Neuroscience Research Institute through leadership of the Computational and Systems Neuroscience theme, focusing on signal processing and system identification, as well as neuromuscular implants, to improve the diagnosis and treatment of a range of degenerative, sensory, and developmental neurological disorders (e.g. soft bioelectronic implants in: *Nature Biomedical Engineering 4:1010-1022*). Researchers have worked on fundamental projects including the "digital fly brain", brain computer interfaces, investigation into the thalamocortical loop in essential tremor, and cervical impedance spectroscopy (EPSRC and BBSRC, ~£0.8M).

Health policy focuses on the interface between social science and systems engineering. The UK Prevention Research Partnership SIPHER Consortium – "system-science informed public health economic research for non-communicable disease prevention" (£1M) is supporting cost-effective action across multiple policy sectors to reduce health inequalities. We are a key partner in the establishment of the Sheffield Alcohol Policy Model, cited in legislation and UK Supreme Court judgements.

Future Strategy. We will continue to develop our research at the engineering, life science and social science interface underpinned by development of multidisciplinary teams focused on challenges informed by clinical and social needs (e.g. our emerging strength in healthcare robotics). We will strengthen our collaborations with Medicine and the Sheffield hospitals as this is critical to translation. We plan to invest in leadership, including via joint appointments - a model that has worked well in our manufacturing research theme.

1.3.5 Community-driven research

In addition to our four challenge-driven research themes, researchers are encouraged and supported to self-organise into areas of critical-mass as driven by sub-discipline research challenges. Research groups are pivotal in this, and bottom-up strategy and support is provided at departmental level. Two examples of such research communities include Materials and Transport.

Materials aims to create and innovate the next generation of advanced materials and processing technologies, to address the global grand challenges of clean growth, future mobility, and a healthy and ageing society.

Over the period, our goal was radical renewal of materials research infrastructure and establishment of a leadership platform for materials discovery and innovation. This was achieved with investment of £44.3M in the Royce Discovery and Translation Centres (EPSRC); £7.6M in the EPSRC National Epitaxy Facilities (EPSRC), and £1.2M in Micro-XCT facilities (EPSRC). Capability was enhanced by two UKRI Future Leaders Fellows (Guan and Cogswell, ~£2.6M).

Advanced metallurgy has made pivotal contributions to clean growth and future mobility. Data-driven design has realised sustainable high-performance alloys for light-weighting in transport (EPSRC, £1.6M); nuclear fusion (UKAEA Chair, £616k); and high entropy alloys (EPSRC, £1.1M). Through SUSTAIN (EPSRC, £1.98M) we are innovating low CO_2 steel production in close collaboration with UK industry, including key discoveries (e.g. in microalloyed steels: *Acta Materialia 161:374-387*). The MAPP EPSRC Future Manufacturing Hub enables us to interface with the powder-based manufacturing sector, leading to co-creation of significant materials-centric UKRI programmes (EPSRC, >£1.1M).

Functional materials has advanced clean growth and future mobility, through innovation and uptake of cold sintering and thick film technology through strategic partnership with Johnson Matthey (JM), and substitution of critical elements for sustainability (EPSRC, £2.2M; JM, £600k). Through collaboration with AVX Ltd. we have developed next generation multilayer ceramic capacitors for electric vehicles, now in pilot production, and published influential underpinning research (*Energy Environ. Sci.* 12:582-588). Nature-inspired processing of materials was advanced through leadership and partnership in Flow Induced Phase Transitions and ECOAT (H2020, ~€622k).

Semiconductors and photonics. We host the National Epitaxy Facility (EPSRC, £7.6M) and a Quantum Technology Capital award for an MBE cluster tool (EPSRC, £2.2M). We are a partner in a CDT for Compound Semiconductor Manufacturing and in a quantum information programme grant (EPSRC, £1.4M). Research on semiconductor devices includes the development of near-infrared photodiodes (e.g. EPSRC, £5.5M; IUK, £264k; H2020, £858k), single photon emitters (IUK £653k), and GaN power electronic devices (EPSRC £871k). In advanced photonic devices and their production we pioneer semiconductor growth methods (EPSRC £777k, H2020, €3.21M), the integration of photonic devices (EPSRC, £2M), and GaN optical devices in the EPSRC Future Compound Semiconductor Manufacturing Hub (£1.6M); and other EPSRC projects (£1.7M).

Future Strategy. In the next period, we will exploit data driven discovery, simulation and optimisation of materials properties and processing, underpinned by life cycle assessment. Within our core research themes, we will address our adopted grand challenges, enabled by our state-of-the-art research environment. We will enable clean growth and future mobility through light-weighting of aerospace components, and material and device innovation for electric motors, engine management and communication.

Transport takes a user-driven approach, developing a close understanding of sector needs through partnership with industry, as well as fundamental research that spans the breadth of engineering. We have targeted growth in the ground and aerospace transportation sectors.

Rail has grown collaborations and leadership through the UK Rail Research and Innovation Network (£1.6M) and a RAEng/Rail Safety and Standards Board Chair (Lewis £0.8M). Research has developed a new understanding of rail track tribology (*Proc. R. Soc. A*. 476:20200057); Lewis was awarded the IMechE Donald Julius Groen Prize and the Institute of Physics "Innovation in Tribology" prize. Strategic investment in infrastructure has enabled unique full-scale test capability for on-track cryogenic cleaning. In close collaboration with our partners, optimisation of end-to-end rail passenger journeys has been sponsored by Siemens, RSSB & Network Rail.

Aerospace is a long-standing strength. We lead the Rolls-Royce University Technology Centre (UTC) in Control, Monitoring & Systems Engineering (established 1993), and the Rolls-Royce UTC in Advanced Electrical Machines and Drives (established 2003), and are a member of the UK Aerospace Research Consortium. Outputs of our research are embedded in the next generation of manufactured products for Rolls-Royce. For example, our tribology research has developed a new understanding of abradable linings technologies with Rolls-Royce (impact case study: *Rolls-Royce aero-engines*). Computational and theoretical fluid dynamics research has explored efficient optimisation and found new evidence to re-characterise transient turbulent flow (*J. of Fluid Mechanics* 764:395 - 427).

Automotive research on optimisation for robust design has developed new methods and workflow tools for cross-function design optimization in collaboration with JLR (EPSRC, £1M) and Ford Motor Company and Ricardo. We have won EU funding to work with European-based partners to expand the reach of our research. We have developed data and service ecosystems to improve mobility in urban areas, developed models and optimisation algorithms for automotive engine parts and created emulators to allow the safe development of autonomous vehicles (>£1M, EU H2020 SETA, COMBILASER and Dreams4Cars).

Future strategy. Our strategic partners, in the UK and overseas, have been key to our success in transport. We wish to strengthen such partnerships and develop new ones, driven by enhanced understanding of the sector's challenges, our industry-scale facilities and ambitious fundamental research in areas such as electrical motors and drives. A recent exemplar of the industry-scale approach is the Laboratory for Verification and Validation – a £9M facility (EPSRC, ERDF, University) hosting purpose-built environmental testing chambers.

1.4 Approach to supporting interdisciplinary research

Fostering a culture of interdisciplinarity is one of our four strategic objectives (Section 1.3) for enhancing our research environment. Our four challenge-driven research themes (Section 1.3.1) act as focal points to drive impact through partnerships across domains and bring together staff across disciplines and with external partners. 195 of our research awards involve collaborations with other disciplines. For example, de Borst's theoretical and computational work on the fracture of fluid filled porous materials influences research in geomechanics and biomaterials (*Mechanics Research Communications 80:47-57*) and Balikhin's research on equatorial magnetospheric waves identifies phenomena hazardous to spacecrafts (*Nature Communications 6:7730*). O'Farrell's research on distributed wireless sensing underpins, NERC funded, world-leading glaciological research on iceberg calving (*Science, 349(6245):305-308*), and Speight's expertise in water system resilience supports a major multi-disciplinary study led by Rhodes University in South

Africa to build resilience for African water resources. We support and model interdisciplinary approaches in the following ways:

Strategic leadership for University Flagship Research Institutes. Pourkashanian directs the University Flagship Energy Research Institute, providing visible leadership for coordinated interdisciplinary work. This includes, for example, work with social scientists in our Management School on lifecycle analysis. Senior staff also hold leadership positions as well as providing scientific inputs in numerous cross-disciplinary centres (Section 4). These facilitate our involvement in large collaborative grants (e.g. TWENTY65 EPSRC Grand Challenge consortium) as well as lead to interdisciplinary outputs such as position papers in influential journals (e.g. *Front. Energy Res.* (03) 2015; *The Lancet* (383)9929, 2014).

Recruitment strategy. We recruit researchers who have demonstrated an ability to work across disciplinary boundaries. All academic appointment panels are chaired by the VP and include significant cross-unit membership to ensure interdisciplinary approaches are valued. Strategic interdisciplinary appointments also cement our links with our partners. Examples include the Faculty of Medicine, Dentistry and Health and the NHS, via INSIGNEO.

Professional support. A challenge-driven research support hub provides bespoke services aligned to our four interdisciplinary research themes (Section 3.1). Its support has been instrumental in coordinating cross-unit funding applications, to growing our manufacturing critical mass activities and securing major BEIS and ERDF investment in research facilities.

Investment to support interdisciplinary research. Our substantial investments in PhD studentships (Section 2.5) include targeted opportunities for co-supervision between disciplines. During the assessment period, 123 PGRs were co-supervised between disciplines within this unit, and 106 PGRs were supervised across faculties. We organise events and provide seed funding to initiate interdisciplinary collaborations, such as a Biomedical Systems workshop with Medicine. We also fund significant infrastructure specific for interdisciplinary research (Section 3.1).

Future strategy. Continued investment in existing successful mechanisms and capitalising on our strategic involvement in interdisciplinary Flagship Research Institutes. We plan to build on our positive experience with manufacturing and healthcare to support other emerging interdisciplinary areas such as circular economy and sustainable development.

1.5 Impact strategy, support mechanisms and outcomes

Our impact strategy relies on four pathways as illustrated in Figure 1.4. Our 11 impact case studies (Figure 1.5) evidence over £4.5bn of economic impact, together with many wider socio-economic benefits. Innovation is coordinated and supported by our Deputy Faculty Director of R&I (Dickman); impact development and opportunities are identified and supported by our Impact Champion (Holland) and an Impact Manager. This leadership and support structure was created during the current submission period.

Figure 1.4 Pathways to impact and support mechanisms

Partnerships. Our AMG has an established subscription-based model, with 160 end-user partners, enabling access to industry-scale research facilities as well as a pipeline of co-created technology-driven roadmaps and projects. With major companies such as Boeing, Rolls-Royce, BAE Systems, Airbus, and Westinghouse, the AMG are core partners in the High Value Manufacturing Catapult (HVMC), where Sheffield is the only university to host two HVMC hubs (AMRC and Nuclear-AMRC), and so to influence and support government policy and major companies and their supply chains. Its success has led to opportunities to work with partners to develop and launch new projects and facilities in Sheffield and in other areas of the UK (Section 3.3), contributing to the University's mission to support the economic development of the Sheffield City Region. Mechanisms for strengthening our partnerships include strategic joint funded chair appointments (e.g. Tiwari Airbus, Todd GKN, Tyas DSTL), visiting academic appointments (e.g. Jackson, Meggitt), and appointing senior leaders directly from industry (e.g. Mayfield, Cordiner).

Challenge-driven research support hub. We frequently co-create research programmes with our industrial partners to tackle real-world challenges to deliver impact. £137M, approximately 20% of our research income, is directly from industry, providing strong gearing and alignment between academic research and industry-relevant impact. Our challenge-driven research support hub has been pivotal in identifying opportunities and supporting bids, in turn enabling the creation of critical mass and laboratory infrastructure leading to impact. This has been very prominent in our Energy and Infrastructure research themes (Section 3.3).

Translational research facilities and the AMG. Our impact capabilities have been further enhanced with the delivery of major outward-facing translational research centres (e.g. Factory 2050, LVV, TERC, see Section 3.3) in areas of underlying research strength in energy, materials, and infrastructure. These facilities mirror industry in scale and complexity, providing industry-relevant research infrastructure. This strategy resulted in opportunities for end-users to de-risk the adoption of novel technologies developed by our researchers. Prime examples of this approach are our case study *BAE Systems* and *Boeing Sheffield.* All case studies are summarised in Figure 1.5.

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Figure 1.5 Summary of impact case studies

Targeted staff support. Core to our impact strategy has been ensuring a greater proportion of researchers are engaged in impactful activities. We established an impact team in 2015 to provide peer-support, mentoring and signposting for researchers who seek to develop impact. The team both responds to researcher requests for support, but also works closely with departments to identify research that has the potential to mature into significant impact. For example, Dr Ben White received tailored support and is now CEO and founder of the University spinout company Phlux and holds a RAEng Enterprise Fellowship.

Researchers have access to specialised IP and commercialisation expertise in the tech transfer team in Research Services, who work closely with our local impact team. The University has an investment fund for proof-of-concept work which makes spinout companies more attractive to venture capital investors. This approach has led to a number of spinout companies being incorporated during this assessment period, including Pyroptik Instruments Ltd, EpiPix, Stratium Ltd and Symemetic Ltd.

We are well supported to develop impact, including £0.9M from the University's EPSRC Impact Acceleration Account (IAA), a Research England Connecting Capability Fund (with Leeds and Manchester) and a generous patent budget. 76 projects, involving 80 staff, have been funded by EPSRC IAA, either as proof-of-concept studies or collaborative R&D. HEIF funding has been instrumental in developing Advanced Metrology for Additive Manufacturing, which resulted in further work and research grants with SMEs (Reliance Precision, Wayland Additive), a Catapult Centre (MTC) and the Diamond Centre Wales.

Future strategy. We plan to build on AMG's highly successful collaborative model, with a strong focus on exploiting the potential of digitisation, including 5G/6G connectivity, and more sustainable production to increase the competitiveness of the UK manufacturing sector. We will broaden this approach, both regionally and internationally and engage more strongly with SME-dominated supply chains. Focusing on our significant potential across our large research base within the Energy Institute, Manufacturing Hubs and translational research centres and facilities, we aim to continue delivering internationally leading impact across all our research themes.

1.6 Open research and research integrity

We strongly support open research approaches. Key to our impact agenda is broader access to ideas, data, and software that also helps to improve the quality of our research, encourages collaboration and avoids duplication, speeds up innovation, and increases the visibility of engineering innovation. 80% of our funding is from public sources so we strive for our research to be accessible to ensure maximum societal benefit. We also emphasise the need to balance openness with the protection of intellectual property, personal data, and national security.

Our strategy for developing an open and ethical research culture is based on the following principles:

- Encouraging behaviours that reward and respect honesty, collaboration, and trust.
- Supporting open access publication to ensure that research derived knowledge is made as accessible as possible.

- Encouraging and supporting actions to ensure all outputs are FAIR - findable, accessible, interoperable, and reusable, whilst taking into account commercialisation, intellectual property rights, the protection of personal data and national security.

A culture of integrity. We have put in place mechanisms to support the above principles, supported by a dedicated Engineering Graduate School Ethics Lead (Section 2.6). All PGRs undertake assessed professional behaviour and ethical conduct training which incorporates the values and obligations of the *Concordat to Support Research Integrity* and includes discipline-specific case studies to allow PGRs to explore ethical judgement and behaviours. New research staff training also reflects this. We have panels of trained ethics reviewers supported by an online system, who can offer advice and guidance relevant to the challenges raised by current research.

Open Access (OA). All staff and students are required to follow University-wide principles of open access for published outputs. Our staff information systems allow support staff and University library staff to provide a mediated service, removing burden from researchers. They can also monitor compliance with external funder requirements. Funding is available for gold OA and publications may also be placed in an institutional green OA repository. To ensure maximum discoverability of our research, we use White Rose Research Online, our shared repository with Leeds and York (green route). The 6,695 outputs deposited over this assessment period were downloaded 644,435 times. This route ensures equity in publishing opportunities regardless of available funding; we publish outputs in fully OA journals, or hybrid where required for funder compliance. Staff increasingly use preprint services (e.g. arXiv) for timely dissemination.

Open Data. The University operates an open data repository ORDA (Online Research Data). All PGRs receive training in developing data management plans, which are mandatory. This ensures they have the knowledge and skills to ensure their data is curated and deposited in an accessible repository, such as ORDA so that it is reusable by the wider community. Recent investments have been linked with developing our capabilities for widespread open dissemination of data. The new Sheffield Urban Flows Observatory (Section 3.3.2), part of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), gathers environmental and infrastructure performance data with the specific intention to share this amongst citizens, companies, and local government to support knowledge exchange, innovation, and policy development. All datasets are open by default (https://sheffield-portal.urbanflows.ac.uk/uflobin/ufportal). We are a founding member and play a leading role in the Data Analytics Facility for National Infrastructure and the National Digital Twin Programme that are aimed at creating an open data ecosystem for infrastructure research.

Future strategy. We will develop mechanisms to ensure that all our research data is openly available within the next 5 years, where appropriate, following the FAIR principles. Our training on data management plans will be extended to all academic and research staff. Specialist training and support will be provided to enable all our staff to develop the skills to ensure that data and other outputs, such as software are findable, accessible, interoperable, and reusable, unless there are legal or contractual constraints. Responsible Innovation training is to be introduced for all PGR and staff to address the ethical dimension of our research and innovation activities in complex, real-world situations. We aspire to lead our discipline in open research and research integrity.

1.7 Overarching future strategy

In the assessment period, we have become one of the largest engineering research communities in the UK, as a result of our strategy for research excellence, challenge-driven research themes and nurturing leadership, targeted growth, translational research infrastructure, strategic

partnerships and impactful innovation. In the next 5 years, we will continue with our successful approaches, in addition to supporting emerging research strengths noted above.

Early in the next period, we will review our four challenge-driven themes, to ensure emerging areas of research are captured, including reflecting on national needs and the international research landscape. We will also review our plans and mechanisms to support community-driven research. In Energy, Infrastructure and Manufacturing we have identified our translational research centres as key drivers for excellent and impactful research and focal points for collaboration and co-creation. We will seek to maximise the effectiveness and impact of our large-scale research facilities, while ensuring their sustainability and strategic leadership via diversification of income and investing in people. We will create a new focus at the interface between our research themes (e.g. Energy-Infrastructure, Infrastructure-Manufacturing) to capitalise on our areas of excellence and aim to lead emerging research areas, while developing existing, and fostering new, national and international partnerships. In Engineering for Life, there are significant opportunities to further address global challenges, by bringing closer together other research communities (e.g. Biology, Medicine and Healthcare) with Engineering acting as a focal point and catalyst. Bottom-up community driven research will also have a pivotal role in driving excellent fundamental research and responding to emerging research with flexibility and agility.

2. People

2.1 Overview

Our people strategy supports two of our four strategic objectives for enhancing our research environment by growing our capability, setting the highest standards of excellence and integrity, and fostering a collegial community, with particular focus on equality, diversity, inclusion and wellbeing.

Our 267 Category A staff includes 24 staff on research contracts who have been identified as carrying out self-directed research and were deemed to be “independent researchers” in line with the definition of Category A eligible staff.

We have delivered on our REF2014 plans; our academic staff whose primary function is to carry out teaching and research (T&R) and post-doctoral or equivalent research staff FTE have increased by 51%, (Figure 2.1) and our PGR by 10%. To capitalise on our growth in research infrastructure and laboratories, we have also invested in technical and support staff (74% FTE increase) essential because of our significantly increased levels of activity.

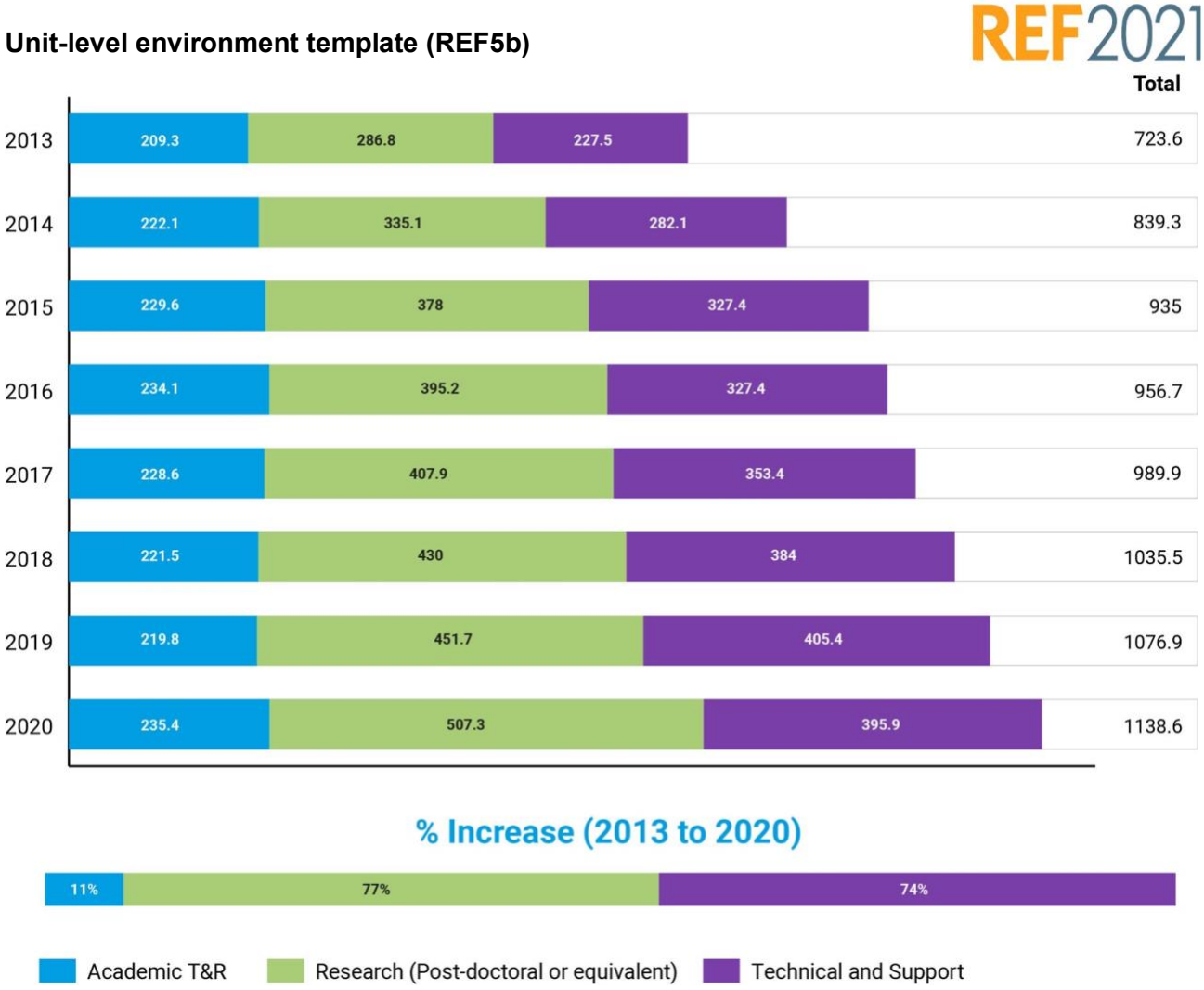

Figure 2.1 FTE and percentage staff changes: academic; research and technical staff

2.2 Staffing and recruitment strategy

Our strategy aims to ensure that we have the excellent research expertise, matched by technical and professional support staff, needed to fulfil our mission and ambition. Our academic recruitment process is transparent about expectations for research outputs, income and impact, which are all explored during selection. Mechanisms include targeted recruitment in areas of challenge-driven research, actions to enhance staff diversity and also planned recruitment to ensure balanced and stable workloads to deliver capacity for research and impact activities. We have recruited 106 academic staff (T&R) and 761 post-doctoral (or equivalent) researchers over the period, as shown in Figure 2.2. In the first part of the assessment period, the proportion of female academics (T&R) recruited was relatively stable. We launched our EDI strategy in 2016, resulting in the proportion of female academics (T&R) recruited rising to 41% in 2019-20 (Section 2.5).

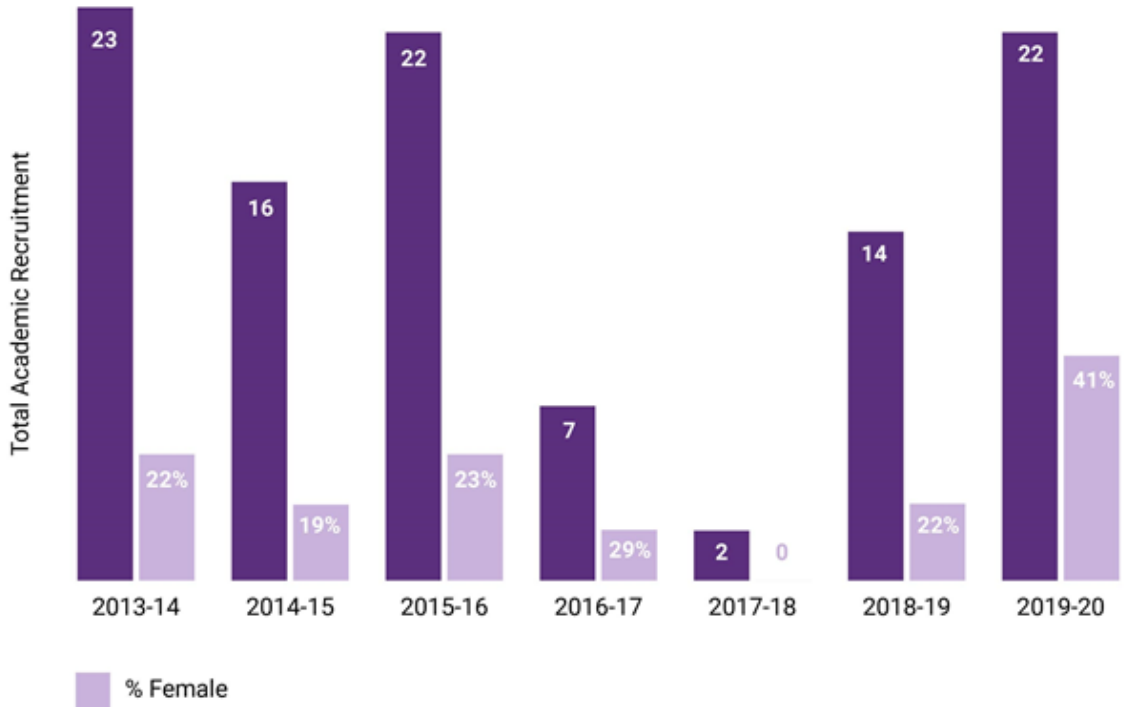

Figure 2.2 Academic (T&R) recruitment over the period - headcount and % female

Recruitment planning. We take into account our challenge-driven research themes, as well as local departmental priorities and we plan collectively for recruitment across the unit. A joined-up approach across departments and AMG ensures we have the expertise so that we can effectively translate our fundamental discoveries into meaningful academic and societal impact.

Selection and training. Responsibility for recruitment is undertaken at discipline level, via a search committee comprising a diverse staff mix with a remit to attract the best possible future colleagues, for example via personal and professional networks, collaborations and proactive contacts. There is active targeting towards under-represented groups and steps are taken to eliminate bias at all recruitment and selection stages including staff recruitment training. All recruitment material is tested to ensure non-gendered language, and we regularly advertise in specialist media targeting women and BAME communities. Our approach was initially shaped to address female under-representation in the discipline, particularly at more senior levels. In the first two selection stages, the proportion of female candidates longlisted and shortlisted is equal to, or higher than, the proportion of applicants. Final selection is on merit, by a mixed panel whose members have all undertaken unconscious bias training; the Chair must also have completed the University training for panel chairs. Over the assessment period, our proportion of female academics increased from 14% to 21%. We now apply many of these recruitment strategies to other under-represented groups to broaden the impact of our inclusive approach.

Our reputation and the support we offer enable us to attract international leaders from academia as well as industry; in exceptional cases we have directly appointed such leaders and in doing so we have consciously sought to improve gender, ethnicity and international diversity. Examples include Professor Mohamed Pourkashanian who now leads the University's Energy Institute; Professor Jim Litster joined us from Purdue; Professor Serena Corr now heads our prestigious Faraday Institute group; and Professor Ashutosh Tiwari holds an RAEng/Airbus Chair in Digital Manufacturing.

Recently, we attracted Professor Genevieve Langdon, from South Africa and Professor Joan Cordiner who joined us after a high-level career in US industry.

Induction. We recognise the importance of effective induction for all new staff. For academic staff with teaching and research responsibilities, we provide a programme delivered at department, faculty and university levels over several months. This programme sets out our strategic ambitions and cultural expectations and includes specific sessions focusing on research, innovation, and impact, and leading and managing people. The programme highlights academics' responsibilities as effective managers of research staff and students, in line with the *Concordat to Support the Career Development of Researchers*. This is backed up by an online Faculty Academic Staff Handbook. The success of our induction programmes is reflected in our biannual staff survey, with 94% having a clear understanding about their role and expectations. The AMG is pioneering an online staff induction system as we now have a number of remote sites (Section 3.3). This allows us to tailor induction programmes to individuals' role and location.

Probation. We support all new academics, with teaching and research responsibilities, with an attractive package including internally-funded PGR studentships, a reduced teaching load and flexible funding to help them integrate into our research groups. Academic probation provides guidance for new lecturers over a period of three years, with regular input from a designated adviser and discussions with the Head of Department (HoD). Our framework for probation ensures consistency of expectations across the unit, with adjustment for discipline variations and individual circumstances. The 2016 University review of probation practices adopted many of the features pioneered in Engineering, for example collective review of cases by HoDs and Faculty Directors prior to Faculty VP sign-off which ensures cross-departmental calibration and informs future objective-setting and review.

2.3 Career development, reward, and recognition

Career development is supported for *all* staff through a formal annual staff review and development scheme, workload planning and specific developmental activities (see below).

To ensure clarity and drive ambition, the University's Academic Career Pathway (ACP) framework was introduced in 2018. It provides a defined, transparent structure for academic (T&R) and research staff from early career through to senior professor. The framework includes clearly expressed expectations, appropriate to each grade in research, impact, leadership, professional standing (including membership of engineering institutions) and teaching (for academic T&R staff), assessed by a range of measures adjusted for different disciplines. The ACP reflects our values of collegiality as well as excellence and ambition. It is now referred to consistently for annual review, probation, and promotion. Expectations are adjusted to take account of part-time working, career interruptions and protected characteristics, and guidelines are in place to mitigate COVID-19 impacts. The ACP has now been operational for one full academic cycle, and staff feedback has been positive. The framework also facilitates movement between pathways where appropriately evidenced, for example Dr Nicola Green has successfully transferred from researcher to academic (T&R). While the ACP provides a clear structure to reward academic research and resulting impact, industry-focussed innovation is less well represented. We are currently leading the development of an innovation pathway on behalf of the University. Whilst important for the whole of engineering, this development is considered particularly important for the AMG.

Support for early career researchers. We have dedicated professional support within the University's "Think Ahead" programme, providing face-to-face and online training for PGRs, postdoctoral researchers and early career academics as well as mentoring programmes, careers

advice, community networks and wellbeing support. 156 colleagues have taken part in the mentoring programme as mentees during the assessment period, 40% of them female.

All postdoctoral (or equivalent) researchers undergo tailored annual staff development review to ensure consistently high-quality, career-focused advice in line with our commitment to the *Concordat to Support the Career Development of Researchers*. Our 2014 and 2016 staff surveys found that the existing review framework was unhelpful, which led to a specific template being developed. Training for reviewers and reviewees was enhanced. Feedback from researchers improved in the 2018 survey, with 83% now saying they found reviews useful. We believe that the improved focus on research career development, from 2016, contributed to the clear increase in successful promotions between 2016-18, as shown in Figure 2.3, illustrating the effectiveness of our career support. A total of 219 post-doctoral (or equivalent) research staff were promoted within the ACP researcher pathway during the period; in addition, 30 of our research only staff were promoted to academic (T&R) positions, and 114 lecturers progressed to senior lecturer.

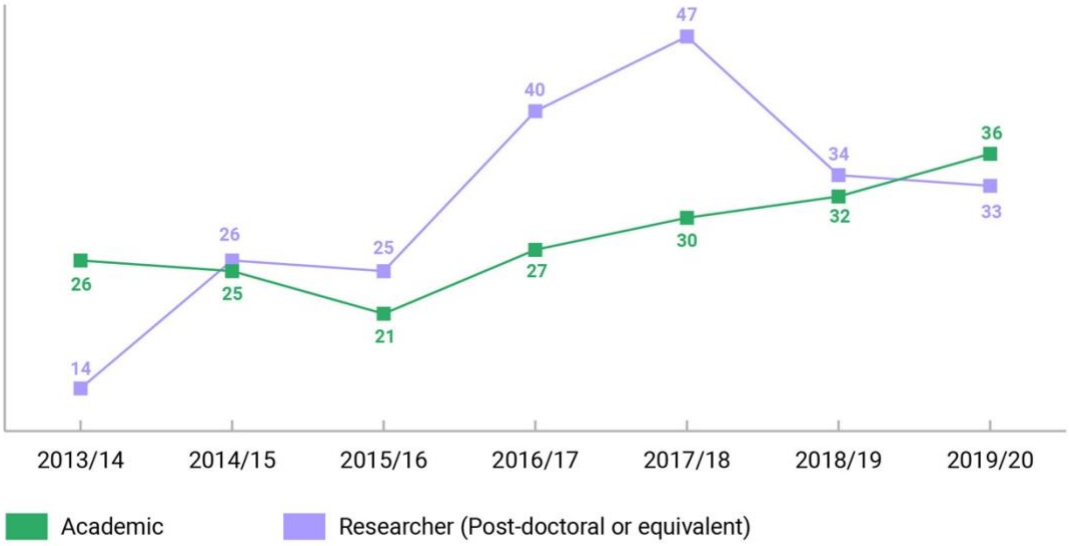

Figure 2.3 Number of early career researchers promoted annually over the assessment period

Employment security is a particular issue for researchers on fixed-term funding, and in accordance with the *Concordat* principles, we actively consider offering open-ended contracts, taking account of our longer-term capability requirements. This policy was introduced in 2012 to provide financial and wellbeing benefits, to demonstrate our commitment to career development, and to retain a more gender-diverse workforce as research shows that employment security is more important for women. The proportion with open-ended employment contracts increased steadily from 19% in 2014 to over 30% in 2020. All staff with over 6 months' employment have the right to access internal redeployment opportunities. Redeployment is often successful, and an average of 164 research contracts have been extended annually during the assessment period.

We support researcher development at all career stages, and in particular recognise the important role of fellowships. Professional staff organise individual mentoring, workshops, and interview training (Section 3.1) to support fellowship applications. This support recently contributed to Dr Ben White securing a RAEng Enterprise Fellowship. We have also developed a distinctive pathway for fellowship holders with guaranteed progression to an open-ended academic position, subject to meeting standard probation requirements. Examples of success by this route include Dr Claire Corkhill (Energy) and Dr Rick Smith (Materials).

Career development for support staff. We are active signatories to the Technician Commitment, encouraging all technical staff to engage in professional registration with bodies such as the IST, IET and Advance HE, and maintain this registration through relevant CPD activities. A number of professional and technical managers have been supported to undertake Higher Apprenticeship programmes for MBA or MSc in Leadership and Management (Section 3.3.3). We also provide bespoke in-house staff development events, which enable networking, as well as specific training.

Leadership Roles are advertised openly to all eligible staff, and selection is by a structured and transparent process. The AMG leadership are in permanent positions, whereas in academic departments, leadership roles rotate enabling colleagues to enhance their skills as well as developing an experienced pipeline. Potential leaders are encouraged to gain experience through membership of executive teams and project groups. Our HoDs have been appointed following this kind of development. At research group level, HoDs work with current research leaders to develop internal talent or identify where targeted recruitment is needed. A total of 236 staff have taken part in institutional leadership programmes. For academic staff, a positive action bias was observed with 31% being female. Participants in our leadership programmes often achieve accelerated career progression. For example, Professor Claudia Mazza was recruited in 2016 as Lecturer, in 2019 became leader of INSIGNEO.

Study Leave. All academic staff are scheduled for one semester of study leave, after seven semesters in post. They are relieved of all duties, except research supervision, to pursue developmental opportunities. All staff scheduled for study leave attend a planning workshop to agree individual plans with their HoD. In the last 4 years, 92 staff have taken study leave, with outcomes including new collaborations, expanding areas of expertise, obtaining new grants and fellowships, and publications. For example, Dr (now Professor) Nicola Morley established a new research area and obtained a one-year fellowship, a DSTL PhD scholarship and a 3-year Leverhulme Trust grant; and Dr (now Professor) Russell Goodall gained a one-year fellowship, a 3-year EPSRC grant and wrote several significant publications.

We encourage and enable staff secondments as ways to develop a better understanding of partner challenges and to develop impact pathways. Examples include staff seconded into government departments (Bruce Adderley from the Energy Institute to BEIS, Professor David Lerner to DEFRA). Opportunities arise directly from our close working relationships, particularly when supporting the Government's strategic decision making in areas such as nuclear and environmental sectors.

2.4 Staff wellbeing strategy

We aim to enable a supportive, healthy, and caring environment. Analysis of the biannual University staff survey allows us to understand issues specific to particular groups. With HoDs taking the lead and with professional support from HR, the Employee Assistance Programme, Occupational Health and external providers, we have taken active steps to raise awareness for supporting colleagues' physical and mental health. We encourage a culture of openness and inclusivity around mental wellbeing and neurodiversity. Examples include a staff and student neurodiversity support group, around 150 staff and managers have undertaken Mental Health Awareness training, with 5 identified mental health champions. Within the AMG, a Health and Wellbeing Community Forum was established to encourage an inclusive working environment. Since the impact of COVID-19, this forum has proved to be particularly important, ensuring that staff feel connected and supported by sharing coping mechanisms and support routes.

Flexible working requests have been agreed for a wide variety of caring and personal reasons, and a growing number of staff are using shared parental leave. Specific policies limit meeting times to agreed core hours to facilitate caring responsibilities. Throughout the COVID-19 pandemic staff have been able to adjust working patterns to accommodate caring or childcare responsibilities. All staff and students have been provided with regular updates and the reopening of laboratories for staff and PGRs in June 2020 was subject to consultation and thorough risk assessment.

Active management of hazards and risks is central for all staff groups. In 2019, we used the HSE Cultural Maturity survey to explore current practices and attitudes. The results showed a very high level of commitment and integrity across all staff groups, with 89% saying that their supervisor takes health and safety seriously and 80% saying their department cares about the health and safety of people.

2.5 Creating an inclusive and diverse community

In 2016 we launched a 5-year EDI strategy covering all aspects of diversity, with an initial focus on improving gender balance. Over the assessment period, the proportion of BAME academic (T&R) staff rose by 1% to 25.4%; BAME research staff rose from 29.0% to 33.9%. Staff declaring disabilities rose from 2.8% to 3.3% for T&R academics and 1.4% to 5.3% for research staff. These increases in declared characteristics were thought to be due in some part to the higher visibility of the value that leaders and managers placed on EDI in the workplace. We are currently developing our 2021 strategy, prioritising more explicit recognition for all aspects of diversity. Our primary focus will be on inclusion, and our action plans will take account of the impacts of different characteristics and circumstances on all our activities.

Our ambitious target to improve female representation was to more than double the proportion of female professors from 5% to 12% by 2020, based on the sector average in 2016, and we aim to achieve 20% by 2025. We have deployed a combination of mechanisms, ranging from outreach activities through to external recruitment activity and targeted support for progression. As a result, the 2020 target has been exceeded, with 16% of our current professors being female. We are strongly committed to the Athena SWAN equality charter, with all departments attaining bronze or silver status and our plans have concentrated on recruitment, retention and promotion of female staff. External funding from a local industry sponsor AESSEAL, helps overcome barriers to female academics' (T&R) progression. This includes a travel fund for conference attendance where caring responsibilities constrain participation. Our success in improving female academic representation is shown in Figure 2.4, with a steady increase in the percentage of female representation at lecturer (24% to 32%) and significant increase in the percentage of female professors (16%) towards the end of the assessment period.

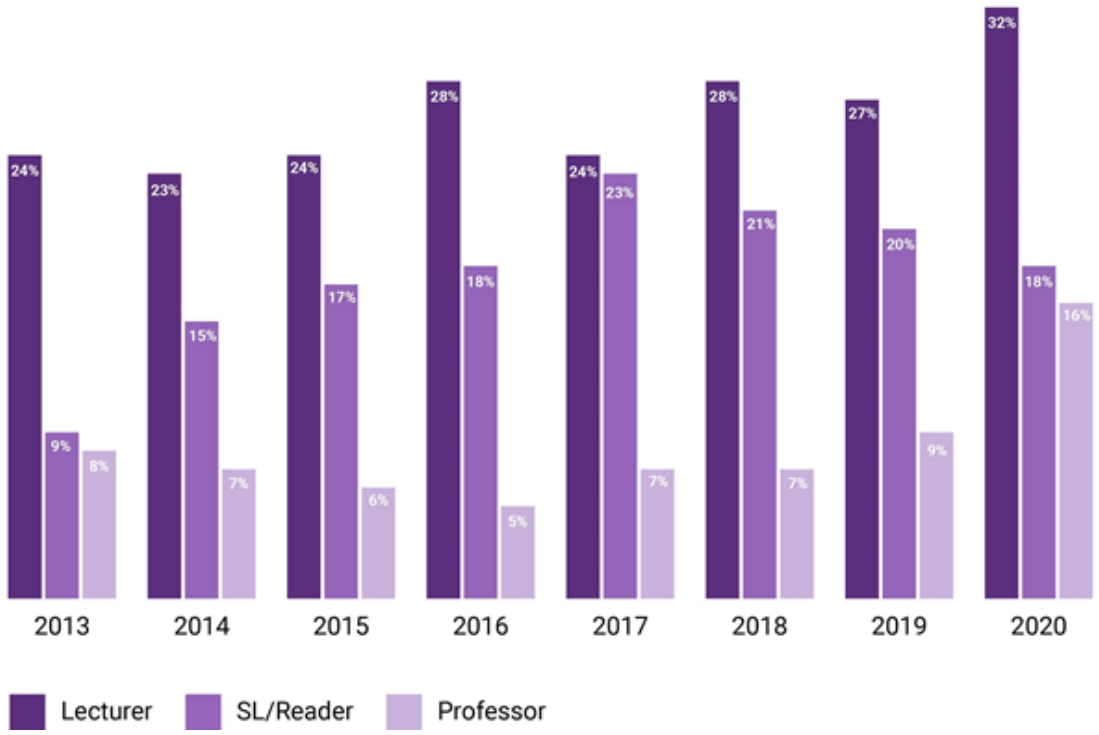

Figure 2.4 Female academic representation over the assessment period

We have delivered unconscious bias training since 2014. Feedback has been overwhelmingly positive, and Engineering is leading and advising on implicit bias training at institutional level. To support equality of access and outcomes in career progression, we have introduced a number of specific practices. Our application of the ACP framework explicitly takes account of the impact of protected characteristics and individual circumstances on achievement. We review academic workloads on return from maternity or parental leave to minimise impact on research productivity, for example by reducing teaching commitments. Female staff are supported to apply to the University's WARP fund which provides financial support for women returning from parental leave, for example paying for research staff. Evidence shows that some staff, often those with protected characteristics, are less likely to put themselves forward for career progression. In response, we have developed new guidance for HoDs in holding supportive career conversations. Some departments have an "encouragement panel"; others hold annual pre-promotion panels which review the CVs of all staff. The most recent staff survey indicates that 95% of our staff have confidence that their employer respects individual differences, and respects people regardless of a range of protected characteristics.

REF submission. Our unit REF working group is diverse in terms of disciplinary representation, gender, and ethnicity. All members of the working group undertook the University's REF-specific EDI training. The work of this group was overseen by a REF Steering Group (reporting to FEB and the Institutional Steering Group) with clear governance and formal reporting.

Written communications, workshops and departmental meetings were developed to ensure all staff understood the eligibility criteria, including those for independent researchers. There were opportunities to declare equality-related circumstances confidentially. Decisions on output reductions due to equality related circumstances were taken at the University level to ensure a consistent institutional approach. Staff absent from the University, for example on maternity,

parental or study leave, were contacted personally to ensure they received the relevant information.

All REF eligible staff are included in our submission, so our focus was on output selection. Outputs were reviewed independently and ranked against clear criteria, with the Working Group acting as a moderation panel. Decisions were taken collectively by the panel and recorded formally. Equality impact assessments at each stage, considered any potential bias against staff with protected characteristics.

2.6 Postgraduate research students

Enhancing the capacity and diversity of our research community and providing a supportive environment are priorities for us and we have worked hard to deliver a significantly improved environment for our PGRs, who make valuable contributions to our research output and outcomes.

Over the assessment period our PGR community grew by 10% to 735; 55% of our PGRs are from the UK, 10% from the EU, and 35% are international, with 83 countries represented within our student body. Our PGR community covers all disciplines in the unit. 20% of our PGRs are co-supervised between engineering disciplines, and 15% undertake interdisciplinary projects with other faculties, demonstrating our capacity and encouragement for interdisciplinary PhD training.

Enhanced resource availability has enabled us to balance the successes which have resulted in higher levels of research and impact activity with our commitment to individual support. The expected supervision load is, on average, 3 PGRs per academic FTE to ensure time for high-quality supervision. We have consistently achieved this expectation over the period.

We aim to promote a culture of excellence, and to prepare our PGRs for careers in industry and academia. The Engineering Graduate School (EGS), established in 2013, coordinates student-facing support and ensures processes are harmonised across the Unit. The EGS takes the lead in ensuring that best practice is followed unit-wide in recruitment, progression and support and that the student voice is heard through student representation, working closely with PGR leads, supervisors and professional staff. Quality assurance of programmes is supported by annual reviews with academic departments to consider specific data (such as submission rates) and discusses topics such as quality of supervision and support for PGR mental health. Feedback is also gathered annually from PGR tutors and managers to help identify good practice and shared challenges and to promote continuous improvement. An example of this is the significant increase in the proportion of PGRs submitting without requesting extensions to their period of study up from 53% in 2014 to 80% in 2020 (Figure 2.5).

The EGS comprises three academic roles and three professional staff. Recognised as an exemplar of good practice, Graduate Schools have now been rolled out across the University. The Director of the EGS led the 2018 review of the institutional PGR progression processes, identifying opportunities to harmonise and improve the way all PGRs are supported and developed.

PGR recruitment. Increased diversity in our PGR community is a current focus. Our PGR community has been 77% male, 23% female over the last 5 years, with female students representing up to 30% in some disciplines. The proportion of BAME PGRs has grown by nearly 50% over the period, and the number of PGRs with a declared disability has almost doubled. All applicants submit a standard application form with supporting evidence and are then interviewed by two academics who have completed unconscious bias training. Regular contact from the supervisor/professional staff aims to integrate them before arrival. All PGRs receive inductions at unit and discipline level. Whilst we attract a diverse pool of PGR applicants, we continually develop

and review our processes to ensure we continue to recruit and support candidates with the greatest potential to succeed, thus taking more than prior attainment into consideration.

PGR funding. We have successfully secured **549 UKRI studentships** to support the recruitment of excellent candidates, including 222 from EPSRC Doctoral Training Partnership, 198 via our participation in 20 CDTs, and 77 as part of iCASE/CASE studentships. Sponsorship by UK industrial partners has increased by 65% over the assessment period. UKRI funding via CDTs and direct commercial sponsorship for PGRs has amounted to £45.6M of support.

Internal investment has supported seven international studentships per year since 2016. We have invested £17.9M over the period, often to leverage externally funded sources such as Chinese Scholarship Council and CONACYT. Internally funded studentships are a minimum of 3.5 years to enable submission within that funded period, contributing to PGR wellbeing and enhancing their working environment and experience.

PGR progress is assured primarily through regular high-quality supervision. Our expectation is regular (and minuted) meetings with supervisors. Formal milestones are:

- Confirmation review at 12 months to confirm PhD candidature and review the student's Data Management Plan - this is done via a committee to provide early experience of defending their research.
- Submission review 6 months before submission deadline; each student is invited to meet with the Head of EGS to plan the final stages of their project and ensure they are positioned for a timely submission. This monitoring procedure was instituted across the unit in 2015 and has led to a significant improvement in the number of PhD submissions without the need to request extensions to their study period (Figure 2.5). Enhanced and consistent support and taking pre-emptive action to mitigate submission delays is a key success of the EGS.

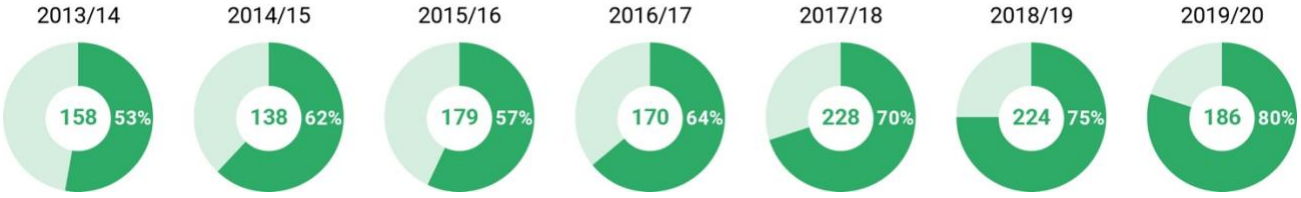

Figure 2.5 Number and proportion of PGR successfully submitting their PhDs without an extension to their period of study.

PGR Training. Through the 'Think Ahead' programme, PGR students access a series of workshops, events, and training sessions to develop their core skills including communication, networking, project management, and academic writing. It is managed by our dedicated Researcher Development Manager whose remit includes development of professional and entrepreneurship skills. Each year PGRs undertake tailored Training Needs Analysis, take stock of their aptitudes, abilities, and future career direction to prepare a training plan.

Nearly 50% of our PGRs have publications, evidencing their highly developed writing skills, demonstrating their contribution to our research output, and giving them a platform to learn critical dissemination skills.

Resources available are targeted by year of study (such as peer mentoring for new recruits) or networks for particular groups, such as students with caring responsibilities. The Researcher

Development Manager also supports student-led activity, working closely with the appointed PGR President and Student Committee. One important contribution of this student group is the yearly Engineering Researcher Symposium, which brings together PGRs and ECRs to present their work. We are unique within the University in having a dedicated ethics lead for PGR students to provide strong senior academic leadership. They are a member of the EGS Board and have a role providing expert advice on research ethics. Our ethics module is mandatory for all our PGRs.

PGR Wellbeing. We are committed to supporting our students' personal and family circumstances with flexible working, parental and medical leave as required. We mirror UKRI policies for our own funded students, providing parental leave stipends and stipends for medical absences up to 13 weeks per year. We support shared parental leave for PGRs where we provide stipends and provide maternity grants for those with no other source of income.

We encourage a healthy approach to taking holidays; PGRs have the same entitlement as academic staff. Each academic department has a PGR Tutor whose role incorporates an element of pastoral support to students. This support is flexible in that an alternative academic may become involved, if for example, a female PGR wishes to discuss issues with a female academic. We have a welfare advisor to provide support and signposting to PGRs with mental health issues. We have introduced pro-rata leave of absence to enable a phased return for students returning from mental ill-health absence. This provision is promoted to students both before and at the start of their studies, with ongoing support and promotion via the academic department and EGS.

2.7 Future strategy

In the next 5 years, we plan to continue with targeted recruitment to strengthen our challenge-driven research themes, enhance diversity and balanced workloads for all staff. Our new (2021) EDI strategy focuses on inclusivity with action plans to examine all research and impact activities. We will continue with our progress in addressing the gender imbalance, via recruitment and progression so that we exceed our current long-term targets. We will broaden this focus to cover all under-represented groups with actions to ensure that we attain a more diverse workforce at all grades. A task and finish group in our EGS is considering PGR recruitment practices especially for applicants from non-standard and more diverse backgrounds, we are committed to implement the outcomes of this group. We are also committed to providing continuing professional development for all PGR supervisors.

3. Income, infrastructure and facilities

3.1 Overview

Income, infrastructure, and facilities have been a major strength and key enabler for excellent research and innovation over the period. **£623M in external research income** over the assessment period, represents a **65% annual increase**. HESA data show we are 2nd in Engineering (including Computer Science) in the UK for our grant portfolio, with a peak spend in 2017/18 when £119.6M put us 1st. A particular highlight is more than doubling our expenditure on low TRL fundamental research (118% increase in RCUK grant awards). Combined with internal investment we produced excellent research outcomes (Section 1.3) and created new world-class research facilities, including 17,760 m^2 of new research laboratories and translational centres.

Our strategy for income generation (Section 1) underpins our four strategic objectives. To deliver this strategy, we focused our professional and peer support on priorities including:

- funder-specific income streams including large critical and/or cross-disciplinary opportunities aligned with national and global societal goals;
- major infrastructure to secure our future competitiveness and to support excellent research and impact;
- dedicated support for research leaders and teams to secure prestigious funding across all career stages.

From 2013/14 to 2018/19 annual research spend per academic staff FTE rose by 65% to £464k. Both total research expenditure and expenditure/FTE ranked within the top 3 of UK universities, demonstrating a leading and sustainable track record (Figure 3.1). Engineering (including Computer Science) at Sheffield rose from 8th to 5th for RCUK support and was consistently ranked in the top 2 for government and industry supported research across UK universities.

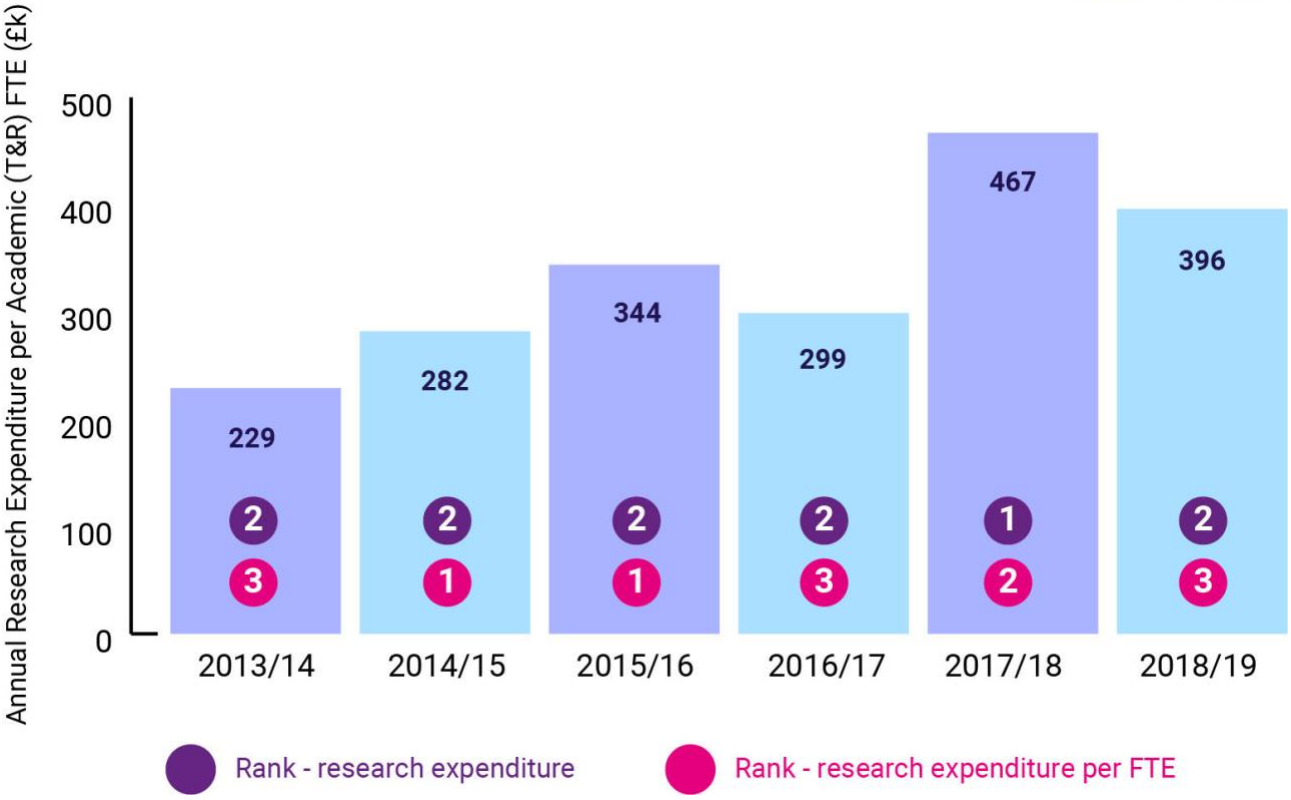

Figure 3.1 Total research expenditure and expenditure per FTE Academic T&R (£k) and rank against UK Universities.

Overall research expenditure increased 65% between 2013 and 2019 (Figure 3.2), with a spike in 2017 reflecting a series of new capital research investments (Section 3.3).

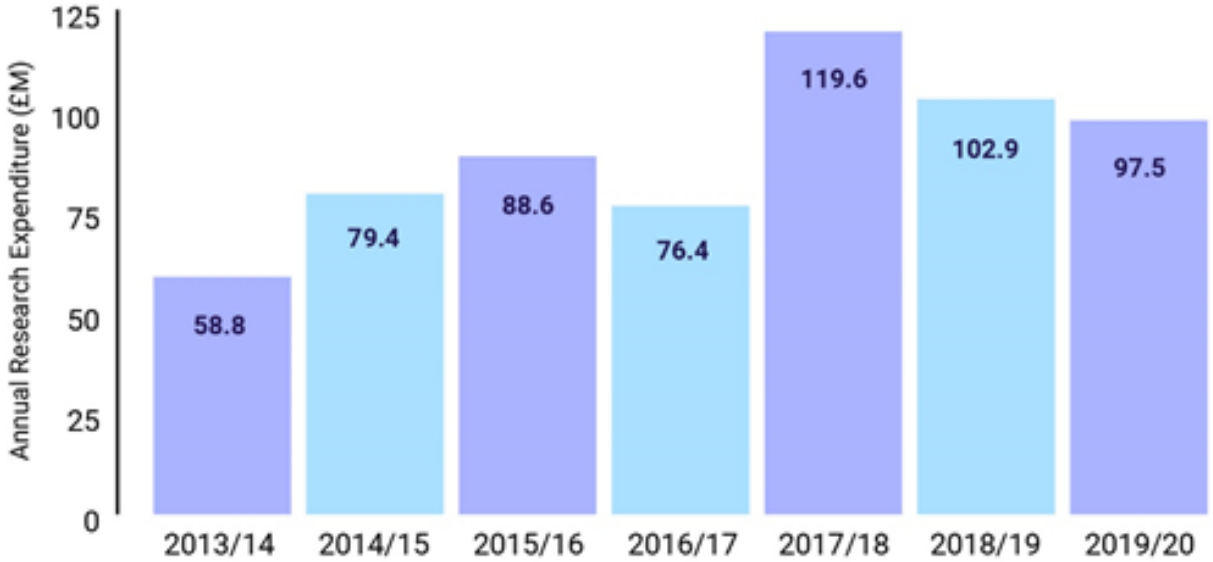

Figure 3.2 Annual research expenditure (£M) over the assessment period.

The breakdown of the growth across income sources is illustrated in Figure 3.3.

- **RCUK funding of £149.4M**, supporting more fundamental research and a number of critical mass activities and national facilities, including the UK Carbon Capture and Storage Research Centre (UKCCSRC), Faraday Challenge, Royce Discovery and Translational Centres, Laboratory for Validation and Verification (LVV), Integrated Civil and Infrastructure Research Centre (ICAIR), Manufacturing Hubs, and EPSRC Grand Challenge, Frontier Engineering and Programme Grants. Annual expenditure from these highly competitive

awards rose from £13.3M to £29.2M, a 120% increase, and the proportion of RCUK spend within our overall expenditure increased from 22.5% (2013) to 30.3% (2020).

- **£247.8M income from UK government** sources, focused on translation and impact, including significant capital investment and revenue funding via BEIS, DECC, Catapult, Regional Growth Funding, IUK (Section 3.3). Support for collaborative R&D via IUK/BEIS ranged from large collaborative programmes (e.g. Aerospace Technology Institute) to 58 Knowledge Transfer Partnerships. Annual expenditure from the UK Government rose from £19.2M to £34.8M, an 81% increase.
- **Commercial income (UK and non-UK) of £136.8M** resulted from the growth of both established and new partnerships across manufacturing, aerospace, energy, pharmaceuticals, transport, and infrastructure sectors (Section 3.2), underpinned by investments in large scale and translational infrastructure.

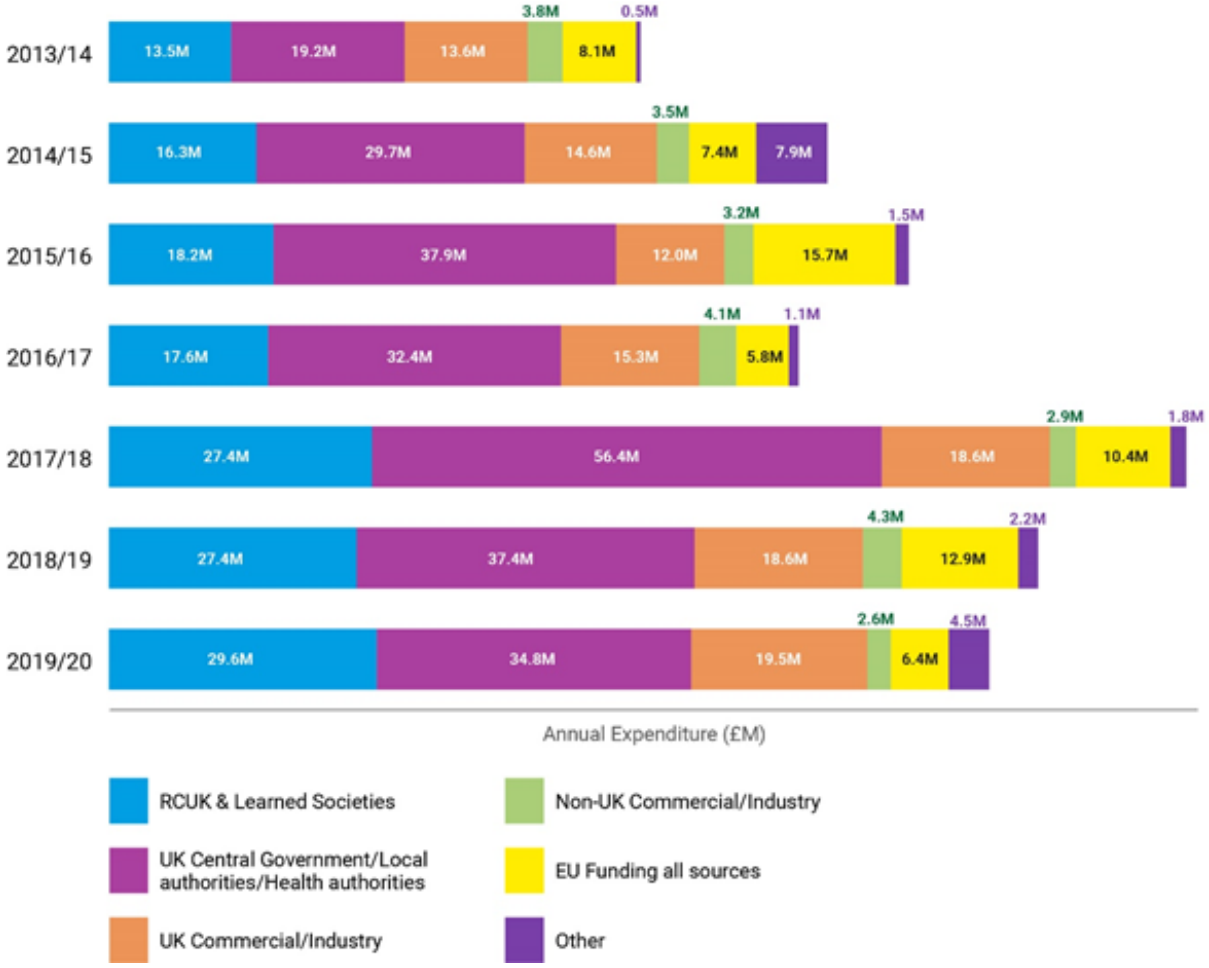

Figure 3.3 Annual expenditure over the assessment period by funding source.

In the assessment period there were ten large research awards >£5M, 34 awards in the £2M-5M range and 52 staff were awarded externally funded research chairs, research and industrial fellowships reflecting our focus on supporting larger, multi-institutional funding bids and our focus on enhancing research quality and the capabilities of our staff.

Professional support. Growth in income has been enabled by enhanced support for funding applications. Research support hubs have 25 FTE dedicated staff across academic departments, and the AMG, together with our multidisciplinary challenge-driven hub supporting our four priority research themes. This to a ratio of around 1:10 FTE professional to Category A staff providing a strongly supportive environment.

Hubs provide pre-award and implementation support, tailored to the funding scheme and applicant's career stage, including proposal development, costing preparation, training on responding to reviewers' comments and organisation of mock interviews. Support for early career academics includes bid writing, peer review workshops, institutional funding for PGRs and technical staff. Support for fellowships includes mentoring from senior colleagues, reviewing of applications and reviewers' comments and interview preparation. For more experienced colleagues there is dedicated, industrially experienced, support from the challenge-driven hub to develop major translational proposals (£2M-£30M), with significant project coordination (up to 50% FTE) over 6 to 18 months. This support has resulted in a number of large awards aligned to our challenge-driven research themes and strategic objectives (EPSRC Manufacturing Hubs, ERDF bids). Processes are in place for swiftly securing internal co-investment for major capital projects, enabling the timely decisions essential to securing £19M ERDF contribution for the delivery of Royce, LVV and ICAIR (Section 3.3). In addition we organise regular workshops to foster and support new capital infrastructure ideas and needs across all scales.

In summary, the increase in funding over the period reflects the development of a more experienced staff profile with the proportion of staff at senior lecturer and professorial grades increasing from 26.3% to 34.8%, and 37.1% and 41.9% respectively, the recruitment of a number of exceptional research leaders, and enhanced, consistent professional support focussed on our priority areas: larger multidisciplinary and collaborative grants, infrastructure investment, and targeted individual support for fellowships and studentships.

3.2 Research income (non-capital)

Our leadership across engineering disciplines is demonstrated through **large multidisciplinary and collaborative** awards, and hosting of **critical mass activities** and **networks**. Strategic investment in facilities, particularly large scale and translational (Section 3.3), has allowed us to drive complex challenge-driven research across our themes aligned with the UK's strategic needs (Eight Great Technologies, Industrial Strategy, Net Zero).

In **Energy,** we lead the UK Carbon Capture and Storage Research Centre (UKCCSRC, EPSRC, £1.9M, +8 HEIs) and Prosperity Partnership with Siemens (EPSRC, £2.6M, +2 HEIs). We are major contributors to the Faraday Challenge, leading FutureCat (£3.2M, +5 HEIs) and partners on four other Faraday projects (£8.4M over 4 awards).

Our **Infrastructure** theme hosts the TWENTY65 Grand Challenge Consortium (EPSRC, £2.4M, +5 HEIs) building on our track record of platform grants in water engineering since 2001 (EPSRC, £1.2M, 2011-2016), led the CENTAUR project (H2020, £477k) and leads the Pipebots programme grant (EPSRC, £2.5M, +3 HEIs).

In **Manufacturing,** we lead two EPSRC Future Manufacturing Hubs (Advanced Powder Processes, MAPP, £4.8M, +5 HEIs and Electrical Machines, FEMM, £6.3M, +2 HEIs), and partner on a further five (Photonics, Semiconductors, CMAC, Metrology and SUSTAIN). We lead EU MMTech and AMOS (H2020, ~ £1M) projects developing materials for additive manufacturing and applications in aerospace repair.

Our **Engineering for Life** theme leads the MultiSim project (EPSRC Frontier Engineering, £5.6M) developing a multiscale modelling framework for the human musculoskeletal system. INSIGNEO remains at the heart of the EU Virtual Physiological Human initiative with >£4.8M income from the EU (e.g. VPH-SHARE, MySpine, Mobilise-D, Back-Up).

We lead EPSRC programme grants, large awards, and networks (and partner on many others):

- Designing Alloys for Resource Efficiency (DARE, Programme Grant, £1.6M, +3 HEIs), SUBST - Substitution and Sustainability in Functional Materials and Devices (£2.2M), Digital Twins for Improved Dynamic Design (Programme Grant, £1.4M, +5 HEIs) and Engineering Nonlinearity (Programme Grant, £1.1M, 2013-2017, +4 HEIs).
- EPSRC Network and Networks Plus grants: UK Acoustics (£1.4M, +10 HEIs), as well as Engineering Complexity Network Resilience, JUNO Network for Japan-UK Nuclear Opportunities and CommNet II (~£940k).

Fellowship income (UKRI, EU, RAEng) was in excess of £18.5M, supporting UKRI Established Career and ERC Advanced Fellowships, Early Career/Future Leadership Fellowships and more impact-focussed RAEng Enterprise and Industrial Fellowships (Section 4.5).

Industrial income over the census period was £137.3M with further support leveraged through **collaborative R&D programmes** (UK government,IUK, BEIS). Highlights include:

- Industrial income from AMG's partners in excess of [text removed for publication].
- Collaborative R&D projects across manufacturing including: [text removed for publication], Advanced Manufacturing Supply Chain Initiative with Laing O'Rouke ([text removed for publication]), additive manufacturing projects with GKN (HORIZON, DAM, AIRLIFT, [text removed for publication]), Landing Gear of the Future with Safran ([text removed for publication]), and Aerostructures: Factory of the Future with Spirit AeroSystems ([text removed for publication]).
- Electrical machines and drives (energy, transport) secured [text removed for publication] industrial income (including [text removed for publication]) with five research centres with co-located industry staff, together with collaborative R&D projects [text removed for publication].
- Our Energy Institute secured collaborative R&D across conventional combustion and CCUS [text removed for publication] (IUK, BEIS) and industrial income [text removed for publication].
- Our bioengineering and biomanufacturing activities secured [text removed for publication] of industrial income (including [text removed for publication]).
- Partnerships across rail secured [text removed for publication] income (including [text removed for publication]).
- In infrastructure and environment, industrial income from water research was [text removed for publication] (including [text removed for publication]).
- During the assessment period, 58 **Knowledge Transfer Partnerships** (£9.8M) enabled collaboration with 70% SMEs, 25% in the Sheffield City Region.

3.3 Infrastructure and facilities

Staff have access to an extensive range of major laboratory facilities located across the city campus, at the Advanced Manufacturing and Sheffield Business Parks, and at additional sites remote from Sheffield. Our core infrastructure comprises 38,696m^2 of high-quality laboratory space and over 5,900m^2 of dedicated PGR office space, of which 70% has been refurbished or newly built over the assessment period. In 2014, the University secured 50 acres of land on the Sheffield Business Park, enabling significant expansion of translational research facilities (Figure 3.4).

Infrastructure has been enhanced to: (i) expand capacity in areas of strength; (ii) support strategic new appointments; and (iii) support areas of research with the potential to make significant contributions and to generate impact. Research infrastructure programmes of £255M (~£123M buildings, and ~£132M equipment) have been completed through internal investment, UKRI, UK Government (HVM Catapult, Growth Deal, BEIS, DECC), ERDF and industry funding.

Figure 3.4 Location of new engineering facilities, 2013-2020

3.3.1. Large-scale and translational research facilities

We have invested strategically in translational and large-scale facilities across our manufacturing, materials, energy, infrastructure, and transport themes, enabling partners to access equipment which is either unaffordable or unavailable for research. These facilities allow us to de-risk new processes and approaches with partners, supporting adoption and business investment. Co-location of industry staff ensures effective knowledge exchange and supports the translational process.

Our **Advanced Manufacturing Group** is an exemplar of university-led economic development. Close partnership work with the Sheffield City Region is part of its success. During the assessment period, a focus for AMG's expansion has been cementing the offer across the whole manufacturing value chain (design, fabrication, assembly, and testing), the key threads across this chain (productivity, digital, sustainability, skills), coupled with increasing access to supply chains and regional clusters. AMG's research infrastructure has been further developed through significant in-kind contributions ([text removed for publication]) from partners across the supply chain via machines, equipment, engineering support and software (e.g. DMG Mori, Renishaw, Siemens, Dassault Systems).

Examples of infrastructure at AMG which enables effective impact include:

Factory 2050, the world's first reconfigurable research factory opened in 2016 (4,100m^2, £21.6M, ERDF, HEFCE). It houses a Kuka Titan robotic arm, upgraded with new encoders and sensors to create the world's most accurate large-volume machining robot for aerospace applications. Our Integrated Manufacturing Group has developed smart benches to support workers with manual assembly processes and pioneered the use of AR and VR in manufacturing including maintenance, repair, and overhaul (MRO) operations. The impact case study *BAE Systems* exemplifies the impact potential of the facility.

Composites Press facility. A Rhodes 1,000 tonne press for moulding carbon-fibre reinforced composites was integrated with a KraussMaffei high-pressure resin transfer moulding with a 100kg capacity (£10M, Sheffield City Region). A Staubli Jacquard 3D loom was purchased to support work in the expanding area of composite dry fibre preforming. These new composites facilities supported McLaren in reshoring chassis manufacturing from Austria to Sheffield in 2018, with a new [text removed for publication] manufacturing facility on the Advanced Manufacturing Park, bringing high value manufacturing regeneration to an economically deprived area ([text removed for publication]).

AMRC's **Design and Prototyping Centre** (2,300m^2, £6.1M), completed in 2013, is equipped to support the design process from concept through to fully functional prototypes. A **Training Centre** (5,400 m^2, £17.9M, ERDF, BIS) was built in 2014 to support degree apprenticeships in Manufacturing Technology and degrees in Mechanical and Manufacturing and Maintenance Engineering.

The AMG has extended this successful model to other regions:

AMRC Cymru (housed within 2,000m^2, £20M facility leased from Welsh Government) opened in 2019, is a state-of-the-art applied research centre. We are supporting R&D for anchor tenant Airbus helping to secure future wing manufacturing in the UK. In AMRC Cymru we also develop manufacturing supply chains in Wales, especially in the food and drink sector, with a recent £2M investment for a packaging sustainability centre. In 2020, we played a key role in the UK Government's Ventilator Challenge (Section 4.2).

AMRC North West supports BAE Systems and the North West Aerospace cluster. Operational in rented facilities since 2018, a new £25M 4,500m^2 facility will open in September 2021 on the Samlesbury Aerospace Economic Development Zone (supported in part by Lancaster Enterprise Partnership Growth Deal funding). Key capabilities include MELD, a solid-state additive manufacturing process for large aerospace structures. AMRC NW is leading a new £9.5M project to develop a 5G industrial test bed with BAE, IBM, and regional suppliers.

In **Nuclear-AMRC's Birkenhead** R&D centre (1,000m^2) we are conducting research into modular construction methods for new reactors and decommissioning activities. The facilities are based at

our partner Cammell Laird's site, close to the North West nuclear cluster and the Wylfa new build site in North Wales. **Nuclear-AMRC's Midland** facility will extend capabilities in supply chain management. The team is currently operating in rented facilities with construction of the new £25M facility (HVM Catapult, Derby City Council Local Enterprise Partnership), located next to the Rolls-Royce Innovation Park, scheduled to start in 2021.

We have also developed large-scale facilities for fundamental research:

We are a partner in the **Henry Royce Institute**, the national institute for advanced materials research and innovation. A £44.3M capital investment (EPSRC, ERDF, University) has established two facilities covering discovery (TRL 1-3) and translational (TRL 4-6) research supporting our **materials, manufacturing and transport themes.** In the **Royce Discovery Centre** (1,200m^2, 2020) we focus on the design of new materials with facilities for high throughput discovery, rapid property screening and new process development. In the **Royce Translation Centre** (1,500m^2, 2018) we incorporate advanced powder production and near net shape manufacturing technologies at pilot/full scale. The two facilities work in tandem, enabling low TRL discovery science to be rapidly scaled up, de-risked and adopted by industry. Royce has worked with and provided equipment access to 19 HEIs and 19 industry partners with collaborative R&D programmes across automotive ([text removed for publication]) and aerospace ([text removed for publication]).

The **Laboratory for Verification and Validation** (LVV, 750m^2, £9M, EPSRC, ERDF, University) is a major structural dynamics, acoustics, and vibration testing facility supporting researchers across our **infrastructure, transport, and manufacturing themes**. Opened in 2019, the facility provides unique facilities for dynamic testing of full-scale structures in ambient laboratory conditions, and vibration testing of substantial structures, sub-structures and components in simulated conditions in controlled climatic test rooms (-55°C to +50°C, humidity, wind and rainfall effects). LVV provides a platform for academic research (EPSRC DigiTwin) and research with industry partners.

The **Integrated Civil and Infrastructure Research Centre** (ICAIR, 970m^2, £10M, EPSRC, ERDF, University), established in 2018 is part of the UKCRIC network of infrastructure laboratories. ICAIR contains the National Distributed Water Infrastructure Facility which has internationally leading capabilities for supporting fundamental and applied research on urban water infrastructure. ICAIR contains a unique 2,000m^3 test cell for the study of buried underground pipe network infrastructure, providing a platform for a number of projects (EPSRC Pipebots, Plexus, IUK, water companies). Flexible laboratory space with a strong floor is enabling research on repair, inspection, and maintenance strategies for legacy infrastructure (e.g. concrete, masonry arch bridges, EPSRC £586k) and the design, manufacture, and construction of new infrastructure.

The **Translational Energy Research Centre** (TERC, 1,540 m^2, £12.9M, BEIS, ERDF, University) forms a key part of the University's Energy Institute. In TERC we host the national Pilot-scale Advanced CO_2 Capture Technology (PACT) facilities. We also host 24 pilot-scale permanent test rigs, including state-of-the-art equipment for conventional energy, carbon capture, utilisation and storage, biomass, hydrogen, renewable energy, energy storage and smart grids. Since 2013, more than 74 industrial and 48 academic collaborations, with over 785 test days has enabled development of knowledge-based screening tools to assess new aviation fuels (EU JETSCREEN, US National Jet Fuel Program), processes to improve biomass combustion (Bio FIB, Energy Technology Institute) and process intensification of carbon capture to reduce capital costs (ARTEMIS, BEIS).

3.3.2. Development of core infrastructure

In REF2014 submissions, we planned two major infrastructure projects to deliver enhanced research and teaching facilities for our growing academic staff and PGR communities: (i) the Pam Liversidge Building (Engineering Graduate School Building) opened in 2014 (£18M, including $1M donation from alum Hon. Sir Sze-yuen Chung); and (ii) refurbishment of the Central Wing of our main engineering building ("Heartspace" project, £51.5M) completed in 2020. These projects have delivered over 1,200m^2 of world class laboratory facilities and nearly 1,700m^2 of excellent quality PGR working space.

Additional significant investments in core infrastructure are summarised below, including a number of national facilities open to other HEIs and industry.

We are the main site for EPSRC's **National Epitaxy Facility** (+ UCL, Cambridge) providing high-quality semiconductor epitaxy for custom-designed structures and devices for UK academics and industry. During the assessment period, Sheffield's core epitaxy facilities have been enhanced (EPSRC, £7.6M) and a new £3.1M quantum technologies laboratory has been supported via EPSRC (£2.2M) and the University. In 2019, at the midpoint of the current 5-year contract, the national facility was supporting UK researchers across 23 UKRI grants. Industrial projects include AQuaSec (IUK ISCF Quantum Technology) led by Toshiba developing new quantum communication components.

The **National Millimetre Wave Measurement Facility** (EPSRC, £1M), opened in 2019, is the only millimetre wave measurement system in the UK for characterising integrated on-wafer antennas and microchips. The measurement capabilities offer a significant technological advancement by enabling the stable, vibration-free integration of a probe station to test on-wafer antennas and on-chip devices, which is critical to the development of future millimetre wave radio systems for 5G and 6G wireless networks.

MIDAS is a national user facility supporting research in the management and disposal of radioactive waste. New state-of-the-art materials radiochemistry laboratories were established in 2015 with £3.75M from the University and the Department of Energy and Climate Change (DECC). The facility is the largest of its kind across UK HEIs, with both supervised and controlled areas to handle radioactive materials according to risk, enabling the formulation, design, processing and characterisation of radioactive waste forms and nuclear fuels. This facility enabled the underpinning research for our impact case study *HAW Management.*

We host the **Urban Flows Observatory** (£2M, EPSRC/BEIS), one of the national UKCRIC urban observatories focussing on energy and resource use at the city, neighbourhood and building level. This consists of distributed fixed sensor networks, mobile sensing vehicles, Mobius (environmental sensing), MARVel (built environment remote sensing) and Morca (radio frequency sensing), data extraction tools, data storage, visualisation, and analytical tools.

We have established new facilities for the **characterisation of particles and colloidal materials** including atomic force microscopy and micromanipulation particle testing to improve the understanding of food powder processes from micro to industrial scales ([text removed for publication]). These investments have supported our impact case study *[text removed for publication]* that derived over [text removed for publication] in economic benefit. A £4M investment in the **Diamond Pilot Plant** enables the study of cutting-edge integrated manufacturing processes at industrially relevant scales, including the ability to manufacture high-value formulated products.

Since 2014, our internationally-leading laboratories for the study of processes related to **urban water supply and drainage** have received over £1.1M of investment from EPSRC/EU and UK water companies, including a temperature controlled 4km pipe loop to study hydraulic and biological processes in water supply systems and 240m^2 of refurbished analytical laboratories. These enhanced facilities have been essential to support the research that led to the impact case study *Managing discolouration.*

We have made a number of investments in our **Energy Institute** supporting energy storage research and our partnership with the Faraday Institute. Extensive battery production, characterisation and testing facilities, part funded by EPSRC were completed in 2016. These facilities include new X-ray MicroCT (Zeiss Versa 620, first in UK) with <0.5micron resolution and allow unique in-situ mechanical, environmental, and electrochemical testing for in-situ characterisation of batteries, fuel cells and multilayers. A suite of SGI high performance computers running Emmerson Distributed Control Systems and nHance MODULAR Modelling System software for energy storage research were supported by EPSRC funds.

Tribology is a key enabling science supporting our **manufacturing, transport, and energy themes**. We have invested in additional measurement capabilities including a second Alicona non-contact surface profilometer, a OnTrak rail head tribometer, a portable Laser Induced Breakdown Spectrometer and a Digital Image Correlation system (total £579k). Additional laboratory capabilities including a unique dry ice environment for rail head cleaning developed via UKRRIN funding specifically for rail tribology research. These enhanced capabilities have been crucial in enabling an EPSRC programme grant, an Advanced Fellowship, Centre to Centre project and industrial partnerships. Tribology is a key technology in our impact case study *Rolls-Royce aero-engines.*

Investments have fostered interdisciplinary research in our **Engineering for Life** theme. Biomechanical laboratory facilities opened in 2013 comprise *ex-vivo* biomechanical testing to measure properties at the tissue and organ levels, and *in-vitro* biomechanical testing to measure properties at the cellular and molecular levels. Additional facilities for investigating human movement biomechanics were created in 2015 (EPSRC/EU). Investment in bioanalytical facilities (UKRI, £0.6M) delivered a custom-built analytical facility with state-of-the-art equipment for proteomic workflows for protein and peptide analysis and characterisation of nucleic acids, nucleosides and other metabolites. This facility enables the bioanalysis of multiple cell systems from mammalian to algae and bacteria, supporting our bioengineering and biomanufacturing collaborations across the University, external academics and industry. The Sheffield Collaboratorium for Antimicrobial Resistance and Biofilms (SCARAB) is a new laboratory (IUK, £0.4M) studying how bacteria protect themselves from antibiotics.

Online systems coordinate use of facilities to ensure fair and transparent access and management of technical resources, and visibility of use. Staff and PGRs can request access and support, which is prioritised against agreed criteria and progress monitored with appropriate charging made to funding sources (external and internal).

3.3.3. Technical Staff

Investment in high-quality support staff is crucial for researchers to develop and deliver world class outputs from our physical infrastructure. Currently 395 technical staff are employed throughout the unit, an increase of 168 since 2013. Their skillsets cross our disciplines from mechanical fabrication, to electronic design and manufacture, material characterisation to advanced chemical and microbial analysis. The University is a signatory to the Technician Commitment and the institutional working group is chaired by a unit HoD.

Early in the assessment period we recognised it was increasingly difficult to recruit skilled technical staff. In 2014, a two-year in-house technician trainee scheme was launched. Since 2014, 9 cohorts of multi-skilled technical staff have been trained. In total, 46 trainees have taken part in the programme of whom 41 secured permanent positions. All trainees obtain City and Guilds in their chosen discipline, and a number have gone on to further qualifications, including NEBOSH diploma and degree programmes. Professional development is maintained through professional registration, CPD and established technical career pathways, through which 19 former trainees have progressed to more senior roles.

At the AMG a structured three-year apprenticeship programme provides an entry-level skills pipeline to support research activities while strengthening links with local and regional partners. In the assessment period, 131 apprentices have taken part in the structured professional development programme. Upon successful completion, apprentices progress to a substantive technical position. During the assessment period, 41 apprentices have progressed to permanent positions within AMG.

These two highly successful programmes have ensured that we now have a sustainable technical and skilled support base, also contributing to up-skilling the local economy.

3.3.4. Sheffield's use of wider national infrastructure

Our researchers have made extensive use of UKRI's central facilities such as the Diamond Light Source, Rutherford Appleton Laboratory (CLF) and international infrastructure such as the European Synchrotron Radiation Facility, Ion Beam Centre Helmholtz Dresden, the Canadian Neutron Beam Centre and the Japanese KEK Photon Factory, supporting projects across energy, materials and manufacturing. The value of this usage has been estimated at £11.2M and involved 38 academics.

3.4 Future strategy

Income, infrastructure, and facilities are a major strength of Engineering at Sheffield and are a key enabler for research and innovation over the submission period; our future strategy is to capitalise on this strength. A number of large capital programmes and facilities concluded in the latter years of the assessment period with further programmes starting in the next period (Nuclear-AMRC Midlands, AMRC North West, and a new Sustainable Aviation Fuels Innovation Centre). We envisage major opportunities for research discovery and innovation at the interface between disciplines in alignment with the socio-economic challenges of our era. For example, interfacing our unique environmental testing facilities (LVV) with our excellent manufacturing infrastructure (AMG, Royce), and using our specialised testing facilities (e.g. Blast Engineering, Energy, Infrastructure) to understand new materials and processes under different environments and conditions. Sustainability and resilience of such infrastructure will be key to deliver the UK's carbon targets, hence we will invest further in emerging interdisciplinary research areas to maximise use, while we diversify our sources of income at the same time (e.g. EU, international funding bodies). To strengthen the UK's research base, we will expand on the collaborative aspects of our research facilities (HEIs, Industry), including leadership and management of national facilities.

4. Collaboration and contribution to the research base, economy and society

Promoting research collaborations, nurturing and sustaining impactful research and partnerships form two of our four objectives to enhance our research environment and are embedded throughout our research activities. This is reflected in the collaborations and networks we have created and partnerships we have fostered, leading to increased academic collaborations, industrial engagement, and wider impacts. Support mechanisms encourage and facilitate the acquisition of resources to enable both national and international research collaboration as well as end-user engagement across all our challenge-driven themes.

4.1 Research collaborations

Developing 'best-with-best' collaborations is a key driver of excellence and impact. Our collaborations range from leading international consortia to academic-led partnerships with local SMEs (Figure 4.1) and involve staff at all career stages.

Figure 4.1 Academic and industrial collaboration overview

Collaboration is encouraged and supported by a range of mechanisms. Professional research support, including for consortium building, is available through the challenge-driven research support hub and the AMG bid writing team for large strategic bids. These staff also support the development of interdisciplinary links and networks (Section 1.4). The institutional Partnerships

and Regional Engagement team has excellent links with local government and industry within the Sheffield City Region and facilitate strategic links in addition to providing support for knowledge exchange activities. We have used internal seed funding competitions to initiate collaborations in emerging funding streams (e.g. GCRF) and to develop impactful partnerships. Importantly, collaboration and engagement are encouraged and valued as a core element of the Academic Career Pathway (Section 2.3). The study leave scheme has provided academic staff with time to initiate, renew, and deepen established relationships with HEIs and research users.

International collaborations. We have won research awards involving over 130 international HEIs and over 150 international industrial partners during the assessment period, demonstrating our commitment. For example, we had pivotal involvement in securing a new 5-year EPSRC centre-to-centre grant between Sheffield and the University of Dortmund on nanoscale quantum photonics. INSIGNEO were instrumental in establishing the partnership Sano centre for computational medicine in Krakow, Poland with a €15M EU award which funds ongoing collaboration until 2026.

Sheffield leads the UK Carbon Capture and Storage (CCS) Research Centre (EPSRC). With 10 core and partner institutions, since 2012 it has grown the UK CCS community to over 1,400 members. It runs a core research programme and open funding calls. It interacts strongly with industry through its test facility (Section 3.3.1) and has forged strong international links with CCS organisations in Australia, Canada, the Netherlands, South Korea, and the USA. Its research leadership have participated in several UK government initiatives such as the BEIS CCUS Cost Challenge and the CCUS Council. We are the lead partner in the International Test Centre Network, which aims to accelerate global R&D into carbon capture technologies by sharing knowledge on the construction and operation of large-scale test facilities. We are a partner in the €23M ALIGN CCUS consortium which unites 34 science and industry partners in a shared goal of transforming six European industrial regions into economically robust, low-carbon centres by 2025.

We have been active participants in European collaborations through FP7 and Horizon 2020, participating in 126 projects and leading 17, often with wide international reach. For example, Sheffield's expertise in additive manufacturing and metallic technologies were a key component of the INTEGRADDE project in which Sheffield researchers are working with 25 partners to develop and demonstrate end-to-end Digital Additive Manufacturing solutions.

The AMRC's long-term relationship with Boeing led to a 2016 research programme to translate Sheffield's extensive underpinning research expertise in machining technologies to deliver major cost and material waste reductions in the production of lightweight alloy components. Combining this with our expertise in discrete element simulation allowed Boeing to explore the possibilities of different operational scenarios, leading to the opening their first new-build factory in 30 years adjacent to the AMRC in 2018. The facility has produced components for 737 and 767 aircraft [text removed for publication] (impact case study *Boeing Sheffield*).

National collaborations Over the assessment period we have formally partnered with 66 UK HEIs and 291 industrial organisations. We have led work with the UK research community to set the national agenda. The EPSRC MAPP Hub hosted a 'town hall' meeting in 2020 bringing together all Manufacturing the Future and Catalysis Hubs, Catapults, industry and UKRI to discuss establishing a manufacturing focused beamline at the Diamond Light Source. In 2020, we led community engagement and developed 'Big Ideas' assessments to the EPSRC SET-B panel around Digital Materials from within Royce and Distributed Mega Cities from UKRRIN. Critical mass awards such as EPSRC programme grants (Section 3.2), Faraday Institute awards and CDTs have supported deep, sustained collaborations with national partners in areas of research excellence.

UK academics can access the AMG via the UKRI-supported *researcher in residence* scheme. AMRC operated the first HVM Catapult Fellowship Centre across the HVMC Network (EPSRC, £1M) supporting UKRI and BEIS ambitions for closer working between Catapult Centres and academia. AMRC hosted Clare (Nottingham) and Longstaff (Huddersfield) developing new metrology methods. Current resident fellows at Nuclear-AMRC are Francis (Manchester), Roy (Manchester) and Fletcher (Huddersfield).

Research Networks. Sheffield researchers have led five EPSRC Network or Network+ grants demonstrating acknowledged leadership in their discipline: O'Farrell (communications), Horoshenkov (acoustics), Hyatt (nuclear opportunities with Japan), Styring (carbon dioxide utilisation) and Mayfield (complexity and resilience). These networks have spanned the disciplinary range and have had national and international impact. The JUNO network co-ordinated and enabled the growth of strong UK-Japan collaboration in nuclear decommissioning, addressing challenges common to Fukushima Dai-ichi and Sellafield, engaging over 60 UK and Japanese researchers. The network supported collaboration development for 12 joint projects sponsored by EPSRC and MEXT (Japanese equivalent), through its programme of annual meetings and bi-lateral visits to research and nuclear facilities. The network contributed to the development of the joint UK-Japan research strategy through participation in the annual nuclear dialogue between the UK and Japanese governments, and championed research translation and commercialisation through the DIT Civil Nuclear Showcase. The network also improved public understanding and awareness of nuclear decommissioning through participation in expert seminars such as the Daiwa Symposium 2016 and events such as the TUC Conference 2019, as well as >20 articles in online, print and broadcast media.

The UK Acoustics Network (UKAN) grew from 200 members at its inception to welcoming its 1,000th member in June 2020 with membership split roughly 50:50 between academic and non-academic members. Over 100 UKAN networking events including workshops, conferences, staff exchanges, grant writing workshops and early career summer schools have taken place. UKAN includes 15 special interest groups, ranging from bio-acoustics through to hearing, computational acoustics, metamaterials and an early career researcher group. New research directly or indirectly supported by UKAN include UKRI strategic priority awards such as Physics of Life, Fellowships, Programme Grants and CDTs. A successor £1.4M EPSRC Network+ has been awarded and will run from March 2021 led by Sheffield.

4.2 Engagement with key research users, beneficiaries, or audiences

Our strategy and four pathways for delivering impact are described in Section 1.5. Here we highlight key impacts for our four research themes.

Energy. Our long-term partnership with Siemens-Gamesa is driven by our global research leadership in electrical machines and drives and underpinned by the RAEng Chair (Zhu) and the joint Siemens-Gamesa Renewable Energy Research Centre (S^2GRE). Step-change improvements [text removed for publication] have led to five successive generations of offshore wind turbines with increasing power output from 6MW to 14MW and an associated reduction in levelised energy costs from £157 to £39 per MWh. This technology is incorporated into all 1,049 of Siemens Gamesa's direct-drive offshore wind turbines, accounting for 23% of global offshore wind grid-connected capacity (ICS *Siemens Gamesa*). [text removed for publication]

Our innovative work in nuclear waste immobilisation has led to the design, manufacture, and performance assessment of glass and ceramic materials for plutonium residues and intermediate level waste. This research has developed confidence that these waste packages will be disposable

in a future disposal facility and the surrounding evidence base for the safety case, supporting national policy decision-makers to address a key UK priority. It has had international impact with uptake of knowledge and technology throughout the UK nuclear industry (Radioactive Waste Management, Sellafield Ltd, Costain), the Ministry of Defence, and the US Department of Energy (impact case study: *HAW Management*). This work has been extensively promoted to the public via more than 20 radio and television interviews, over 30 published news articles and online media and a documentary with an estimated reach of 1.1m people.

Infrastructure and Environment. Our unique translational facilities (ICAIR, two UKCRIC facilities, Buxton Blast laboratory) support long-term partnerships with the UK water sector and DSTL.

TWENTY65 Tailored Water Solutions for Positive Impact is an EPSRC Grand Challenges consortium of six UK universities (EPSRC, £3.9M) which aims to tackle the challenge "of sustainable water for all" through innovative social and technical solutions. This Sheffield-led project is addressing the failure of the UK water sector to exploit innovation and engaging national politicians, regulators, NGOs, water companies and their supply chain. Its work has influenced OFWAT's water sector innovation strategy and Boxall has spoken at the all-party parliamentary group for water and a DEFRA water efficiency evidence day.

Sheffield research has provided critical insights into blast load characterisation and bomb neutralisation techniques. A strong partnership with DSTL, underpinned by an RAEng Chair (Tyas), led to these advances in fundamental understanding being translated into life-saving applications for the UK and its defence partners (impact case study: *Blast Protection*). This research has influenced defence and security practices and policies and enabled new technical standards. Applications of our blast research, such as the Fly-Bag aircraft hold liner, have received extensive media coverage.

The UK Research Strategy Community Organisation in Communications, Mobile Computing and Networking (EPSRC) attracted 230 academics and industrialists (75:25 split), representing over 80% of the UK's communications and networking community. Led by O'Farrell, it delivered 17 UK research challenge workshops, 2 international workshops, 1 international conference (Next-GWIN 2018) and 4 PhD schools to over 1200 attendees. Its activities seeded numerous EPSRC awards: standard awards, managed calls, programme grants, fellowships, capital equipment, Prosperity Partnerships and CDTs.

Manufacturing We have strengthened key partnerships with leading manufacturers over the assessment period including Rolls-Royce, Boeing, GKN Aerospace and Airbus. The strategic expansion of the AMG and the new Henry Royce Institute (Section 3.3.1) have supported these partnerships and the development of new collaborations via co-location opportunities, access to key equipment, which is of particular value to SMEs, and enabling translational projects at industrially-relevant scales.

The Airbus partnership on the Wing of Tomorrow/Future programmes is an exemplar of how we work across TRLs with a clear pipeline from discovery to application. Fundamental low-TRL work is delivered via our RAEng Chair (Tiwari) in parallel with a programme of mid-TRL research at Factory 2050 and AMRC Cymru. Low-TRL work transitions to Airbus either directly or via Factory 2050 and/or AMRC Cymru depending on risk. Co-location of staff is key, with Airbus an anchor tenant at AMRC Cymru and David Harra, Head of Airbus Assembly Technology, an RAEng Visiting Professor.

As part of the 2020 Ventilator Challenge UK, the AMRC's Cymru facility was transformed, from joint R&D activities for Airbus wing manufacture into a production hub for ventilator parts. Airbus's

aerospace engineers were re-trained to make medical equipment using 'mixed reality' headsets pioneered by AMRC, combining the real world with interactive holograms. This allowed engineers on the production lines to see every part of the process involved in assembly and even talk directly to a remote support engineer while maintaining social distancing. Discrete event simulation models created by AMRC staff ensured a socially-distanced flow of people around the facility during manufacture. In total, 13,400 ventilators were delivered in 10 weeks, a task which would have normally taken 10 years.

Following a series of highly successful collaborations, including a project that halved the machining time of titanium fan discs, AMRC participated in two Rolls-Royce/IUK-sponsored four-year programmes (SAMULET 2 and 3), [text removed for publication]. SAMULET 2 included High Performance Shaft Manufacturing, which won the Henry Royce Engineering Excellence Award for 2016. In SAMULET 3, the majority of AMRC projects focussed on machining. Proprietary aero-engine alloys were tested for their machinability, then machining methods were matured up the readiness level scale towards the point of mass production. AMRC's machining simulation tools were used to propose significant process improvements. Rolls-Royce's dedicated disc manufacturing facility in Tyne and Wear and facilities in Germany and the USA have benefitted from the manufacturing techniques developed in the two projects (impact case study: *Rolls-Royce aero-engines*).

Academic-led partnerships include our two Rolls-Royce University Technology Centres: Control, Monitoring and Systems Engineering (Kadirkamanathan) and Electrical Machines and Drives (Jewell). Over the assessment period these centres have received [text removed for publication] of core funding with a further [text removed for publication] to fund specific research activities.

The UK's success in manufacturing depends not only on major contractors, but on the large number of SMEs who supply key components. The AMG occupies a pivotal position, having both close partnerships with the major contractors and strong links with SMEs, and an excellent underlying research base in key technologies that can support supply chain development. The Fit for Nuclear (F4N) scheme, funded by the HVMC and developed by Nuclear-AMRC, utilises this position to help manufacturing companies assess and develop their readiness to participate in the UK nuclear industry supply chain. Since 2013, 757 companies from outside the traditional nuclear supply chain have participated in the programme, working with our staff to build their capacity. Over this period, these companies have been awarded 1079 contracts with a value of £76.5M, creating 385 new jobs and safeguarding 780 jobs UK-wide. Building on F4N's success, we are now working with the Offshore Energy Renewable Catapult to bring similar supply chain development to the UK offshore wind sector. Fit for Offshore Wind was piloted in Scotland in 2019, engaging 40 companies, with the project rolled out to the rest of the UK in 2020.

Engineering for Life Healthcare. We engage with Sheffield Teaching Hospitals Trust, the largest single NHS trust in the UK, via INSIGNEO. This partnership also enables engagement with wider audiences and stakeholders in healthcare, to create impacts and disseminate our discoveries. For example, non-invasive in-silico models of cardiovascular pressure have been successfully tested in clinical trials and used to augment catheter guided interventions in coronary artery disease (e.g. Frangi, STH collaboration), hence engaging with clinical and technical staff in the NHS and the private sector.

Innovative tissue engineering research integrating tissue culture techniques with ocular surgery led to the development of simple limbal epithelial transplant (SLET), an improved and lower cost treatment for blindness caused by ocular burns and provided the opportunity to engage with international stakeholders. We have provided skills and treatment strategies to ophthalmologists in

14 countries (in Asia, Europe, North and South America) enabling 1,291 children and adults to date to have their eyesight saved (impact case study: *Saving eyesight*).

The Sheffield Alcohol Policy Model supported policy development for minimum unit pricing (MUP). The model, and its findings, played a key role in the UK Supreme Court judgment ruling in favour of the introduction of MUP in Scotland. The policy was implemented in May 2019 and its effectiveness at reducing alcohol-related harm is being evaluated by the Scottish Government.

4.3 Wider contributions to the economy and society

In addition to the £4.5bn of economic impact described in our impact case studies, the following examples detail additional significant impacts arising from our research, representing wider contributions to the economy and society.

Our research (H2020, COMBILASER), integrating machine learning, data curation, and modelling frameworks has transformed [text removed for publication] (automotive) laser welding process, [text removed for publication]. Further uptake of Sheffield's COMBILASER research by [text removed for publication] (white goods) in Europe and China, and [text removed for publication] (oil & gas) has extended the reach of the impact of our research.

Two streams of our bioprocess engineering research have underpinned improvements in the efficiency of bioprocesses, an increasingly important issue as the number, diversity, and complexity of biological therapeutics being developed increases. [text removed for publication].

Our excellence in composite materials and manufacturing resulted in a partnership with McLaren to deliver an extensive programme of research to improve the performance and processing of carbon fibre reinforced polymer composite components. The success of this programme and the importance of continued close collaboration led McLaren to construct a new [text removed for publication], 7,000 m^2 carbon fibre manufacturing facility adjacent to AMRC which utilises an improved method of manufacture, developed in collaboration with our researchers. [text removed for publication]

4.4 Engagement with diverse communities and publics

As an institution with a strong sense of civic duty and engagement, we believe that engaging with the wider community is a vital strand of engineering research to support our overarching goal of making the world a better place. Our outreach activities aim to interest and inform a broad cross-section of the public; we are particularly keen to engage and excite the next generation of engineers and support their education. In order to develop a more diverse pipeline of engineering talent, many of our events actively target under-represented groups. Engagement is achieved through virtual activities, the provision of educational resources, demonstrations, and communication via new and traditional media. Activities are often led by teams from large research projects, drawing in our ECRs and PGRs.

The Flashy Science website developed by materials scientists Allwood and Dean, provides interactive, virtual experiments linked to common school and university curricula. They allow school and university students to 'learn-by-doing' where local experimental facilities may not be available. This activity has been commercialised and is currently used by 250 groups internationally, and 20,000 individual users. We also run a programme of public activities (Engineering Imagination - held online in 2020, Exploring STEM for girls) and contribute to local and national events (Sheffield Festival of Science and Engineering, Engineering Week -Tomorrow's Engineers, This is Engineering Day, Big Bang Fair), aimed at encouraging young people, especially women to

consider engineering as a career option. A number of residential summer schools are run to encourage young people from under-represented backgrounds to enter the engineering profession. We have a have a dedicated 3-person STEM/Outreach team (AMG) who deliver a bespoke programme of activities, group tours and work placements to schools in the region.

Our researchers have contributed to public debate via the broadcast (BBC/ITV/Sky/BBC World Service/BBC Radio) and print media in a wide range of topics such as nuclear waste management, reactor failures, CO_2 shortages, robotics, plastics, blast protection in aircraft, and bio-pesticides. A small number of staff also contributed to scientific documentaries in their areas of expertise.

4.5 Contribution to the sustainability of the discipline

We contribute to the sustainability and vibrancy of Engineering nationally and internationally in diverse ways. Academic citizenship is recognised in the Academic Career Pathway ensuring internal as well as external recognition for work undertaken peer reviewing, providing editorial services, organising conferences, serving on advisory boards, and contributing to learned societies. Our work allocation model provides protected time for scholarly activities. Often research sabbaticals are strategically devoted to providing leadership for the discipline.

Editorships and conferences. Our staff are editors on some of the leading journals in our disciplines. During the assessment period staff have served as editor-in-chief or editor for 25 journals including: *FUEL* (Nimmo); *Journal of Geophysical Research*: Space Physics (Balikhin); *International Journal of Systems Scienc*e (Kadirkamanathan); and *Theoretical and Applied Fracture Mechanics* (Susmel). Staff have served on a further 90 national and international journals as associate editors and on editorial boards.

We have been active on the organising and programme committees of over 50 national and international conferences and workshops including chairing and organising Computing and Control in the Water Industry 2017 (Boxall), 16th International Symposium on the Science and Technology of Lighting (Wang) and the 2018 IEEE Sensor Array and Multichannel Signal Processing Conference (Lu). We have hosted a range of events in Sheffield, providing additional opportunities for our researchers and PGRs to network with experts in their fields. Our CDTs have also initiated and hosted national student conferences to provide a supportive environment to develop presentation and networking skills.

Recognition. A number of staff have been recognised by the Royal Society and Royal Academy of Engineering for their work. J Rodenburg was elected a Fellow of the Royal Society; Cordiner, Dwyer-Joyce, de Borst, Rainforth, Viceconti and Zhu were elected Fellows of the Royal Academy of Engineering during the assessment period. Other colleagues have been active in the leadership of learned societies, for example as Vice President of the IMechE (Beck), President of the European Society of Biomechanics (Reilly), and President of the International Society of Information Fusion (Mihaylova). Stand-out prizes include the 2019 IEEE Industry Application Society Outstanding Achievement Award (Zhu), the 2019 Nigeria Prize for Science (Wang), the IMechE Donald Julius Groen Prize (Lewis) and the Institute of Physics "Innovation in Tribology" prize (Schirru), Grand Prize of the Japanese Society for Computational Engineering Science – JSCES (de Borst), Minerals and Mining Chapman Medal - Institute of Materials (MacNeil), and Group Achievement Award (Geophysics) by the Royal Astronomical Society (Balikhin).

Advisory Boards. Tiwari, Corr, Heffernan and Gandy serve or have served on EPSRC Advisory Boards; Boston, Law, Majewski, and Smyl serve in early career forums. 117 staff have been Full/Associate EPSRC college members. We actively contribute to diverse national and international standards boards including BSI committees for the coding of picture, audio,

multimedia and hypermedia information, safety footwear, green roof substrates, and ASTM standards for cements, as well as friction and wear.

Fellowships often underpin our strategy for industrial collaborations, fundamental research themes and joint appointments. Hyatt (Nuclear Decommissioning Authority – Radioactive Waste Management), Lewis (Rail Safety and Standards Board - Wheel/Rail interface), Pilakoutas (Twintec - Sustainable Fibre Reinforced Concrete), Tiwari (Airbus – Digitisation for Manufacturing), Todd (GKN Aerospace – Advanced Structural Metallics), Tyas (DSTL- Protection Engineering against Blast), and Zhu (Siemens-Gamesa - Wind Power Generation Systems), held Royal Academy of Engineering Research Chairs during the assessment period.

De Borst held an ERC Advanced Grant (PoroFrac, £1.8M) and Minev an ERC Starting Grant (IntegraBrain, £1.3M). Dywer-Joyce, Guymer and Worden received EPSRC Advanced Career/Leadership Fellowships during the assessment period. EPSRC Manufacturing/HMVC Fellowships were awarded to Tiwari and Willmott. EPSRC Fellowships were also awarded to Corkhill, Cross, Douterelo Soler, Kessarwani, Patwardhan, Rodenburgand and Thorpe. Goodall, Keylock, Lynsdale, Morley and Wong were awarded RAEng/Leverhulme Trust/Royal Society Senior Research Fellowships and Boston a RAEng Research Fellowship. Campbell was awarded a Royal Society/Dorothy Hodgkin Fellowship. ECRs have also accelerated their career development through prestigious fellowship awards including UKRI Future Leader Fellowships (Guan, Cogswell). To support our impact agenda, Brown, Green, Hathway, and Smith were awarded RAEng/Royal Society Industrial Fellowships and Hartley and White were awarded RAEng Enterprise Fellowships. Fifteen Marie-Sklodowska Curie Individual Fellowships were awarded during the assessment period.

Collaborative PGR training. The strength and depth of our research in particular areas has been reflected in our leadership and participation in competitively funded early-stage researcher/doctoral training programmes, including EPSRC Centres for Doctoral Training/Industrial Doctoral Centres and EU Initial Training Networks. Over the assessment period, 20 EPSRC-funded CDT/IDCs and 11 EU ITNs have been active at Sheffield. We lead CDTs/IDCs in Advanced Metallic Systems, Interdisciplinary Energy Research, Machining Science, Energy Storage and Integrated Tribology. We co-ordinated seven ITN training networks (QUICs, Endure, INSPIRATION, DyVirt, PROMIS, SPINNER, Wavecombe), and partnered in four others (Hytech, DuRSAAM, CReaNet, B-QMIND). Most have been collaborations with other major research groups at national and international research-intensive universities, often with significant industrial partnerships.

4.6 Future strategy

We are immensely proud of our existing collaborations as well as our contributions to the UK and the engineering discipline. Our growth in impact activities over the period has enabled us to extend our collaborations and reach and disseminate our discoveries and impacts to our peers as well as to diverse communities and the public.

We plan to enhance our existing four pathway model of engagement. We will strengthen our existing long-term partnerships in the manufacturing area by exploiting the opportunities in

digitalisation and more sustainable materials and production processes. In Energy and Infrastructure we plan to develop new strategic long-term partnerships utilising our recent investment in industrial-scale translational research facilities. In Healthcare we will aim to engage more fully with the NIHR and also at the international level with our excellent European networks.